A NEW APPROACH FOR ADAPTIVE POWER SYSTEM STABILIZERS

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CERTIFICATE

Certified that this work on 'A NEW APPROACH FOR ADAPTIVE POWER SYSTEM STABILIZERS' by Goutam Bandyopadhyay has been carried out under my supervision and that this has not been submitted elsewhere for a degree.

April, 1986.

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ABSTRACT

In this thesis we have considered the problem of designing adaptive power system stabilisers for a single machine and a simple multimachine power system . The solution proposed is different from those which are available at present in the literature.

The conventional non adaptive PSS work satisfactorily so long as the system operating conditions do not change significantly. But in practice,loading conditions and therefore, the operating conditions,do change significantly. So, there is need for design of adaptive PSS. Some work on adaptive PSS design has been reported earlier [28-30]. They all involve on-line identification of system parameters. This makes the schemes rather complex. The problem of implementation of these schemes on actual power systems has not been investigated to a satisfactory degree.

In the method proposed here, a set of PSS is designed. Each PSS in the set is designed for a particular operating conditions. All the PSS in the set are simultaneously operating, in parallel. The control signal for stabilization is obtained as a weighted sum of the output of these PSS. Thus, in operation, only these weights are to be adjusted, in accordance with the operating conditions obtained. Proposal have been made for determination of the weights and their efficacy established.

The proposed scheme give performance superior to the conventional nonadaptive PSS for changing operating conditions. At the same time, it avoids the complexities in the traditional adaptive PSS design and is simple to implement.

The proposed algorithm has been tested in detail, for various operating conditions, for single machine infinite bus system. Its applicability in multimachine system has been confirmed by studying its application to a typical 3 machine 9 bus system.

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LIST OF SYMBOLS

Symbol	Details
Δ	Prefix to denote small changes about the operating point
o	Subscript to denote the value at operating point
t	Time in seconds
ω_o	Synchronous angular velocity in rad/sec.
ω	Instantaneous angular velocity in rad/ sec.
∂	Instantaneous rotor angle
v_t	Machine terminal voltage
i	Armature current
V_d, V_q	Direct and quadrature components of V_t
i_d, i_q	Direct and quadrature components of i
R	Transmission line resistance
X	Transmission line reactance
X_d	Direct axis synchronous reactance
X'_d	Direct axis transient reactance
T'_{do}	Open circuit field time constant
H	Inertia constant in seconds
T'_e	Electromagnetic torque
T_m	Mechanical torque input
X_1	State variable associated with voltage-regulator
T_R	Voltage-regulator time constant
K_R	Gain of voltage regulator
T_e	Time constant of exciter system
E	Voltage at the infinite bus system
I_a	RMS value of i
I_d, I_q	Park's components of I_a
E_{fd}	Correcting feedback signal from output of exciter

Other symbols used in the text are explained as and when they are introduced.

CHAPTER 1

1.1 INTRODUCTION

During the past two decades there has been continuous effort to improve power system transient and dynamic stability characteristics. Use of fast acting static exciters and high gain AVR has become a universally accepted practice. They improve system transient stability. However, it has been observed that these excitationcontrol systems introduce negative damping, making the system dynamically unstable, in some cases. The low frequency oscillations which are typically in the range of 0.2 to 2.0 HZ are due to periodic interchange of mechanical kinetic energy between the rotors of power generating stations, caused by differences between speeds of machines. If a control signal can be applied which reduces the difference in speed, these oscillations can be damped out. So a feedback of speed error can act to control the speed and provide damping. From the above argument, speed has become the most common and popular stabilizing signal. Acceleration, accelerating power and frequency are the other signals which can be used for the same purpose. Comprehensive study of use of all the popular stabilizing signals are available in the literature [1,47].

In the foregoing, it has been noted that a stabilizing signal is required for the excitation control loop. The

auxilliary controller, known by the name power system stabiliser (PSS), receives the stabilizing signal from rotor speed, accelerating power or frequency and provides corrective signals at the input of the excitation system in order to damp out the oscillations in the system. Since we are concerned with system response to small scale disturbance, PSS can be designed using the linearized model of the power system about an operating point.

1.2 PSS DESIGN OBJECTIVE

As already mentioned, the reason for instability in power systems is the negative damping introduced by high gain excitation control system for improvement of transient stability limit and system voltage regulation. Since we deal with a linearised system, where negative damping can be viewed as being due to positive real part of a complex eigenvalue, the objective of PSS design will be to shift the unstable complex eigenvalues to appropriate locations in the left half plane.

1.3 SYSTEM MODEL

The model considered consist of a single machine connected to an infinite bus through a transmission line, (Fig. 2.1). Development of state equations for this model is given in chapter 2 and Appendix A-1. We also consider in this thesis a 3 machine, 9 bus system shown in Fig.A 4.1.State equations for this system are developed in chapter 4.

1.4 OPERATING CONDITIONS

The real and reactive power outputs and the terminal voltages of the generators are taken as operating conditions for the design of PSS. As the load changes the real and reactive power generation changes, so the PSS designed also should change. In the ideal case for every operating point there must be a PSS to provide proper stabilization.

1.5 DESIGN METHODOLOGIES

1.5.1 Non Adaptive

In this design methodology the PSS structure and parameters, once designed, do not change with change in operating conditions or in system configuration. Such a PSS gives good results only if the system operating condition do not change much from that used for PSS design. A rather extensive list of methods falling into this category is available in the literature. Here only a few of them are discussed.

The various methodsused for PSS design can be broadly classified into two categories, 1) those based on classical control theory and 2) those based on modern control theory.

The problem of low frequency undamped oscillations was investigated by De Mello and Concordia [2] through the

concept of synchronizing and damping torques produced in the system at the oscillation frequencies. One is proportional to the difference in rotor angle of a machine to that of the system and is called the synchronizing torque; the other is proportional to the speed of a machine around system speed and is called the damping torque. In Ref. [2] the authors used the single machine infinite bus model to explain the effect of the excitation system on the rotor oscillations. A design method for PSS using frequency response technique was suggested to improve damping torque without affecting synchronizing torque Bollinger and Laha [3] used the root locus method of design to shift the rotor oscillation eigenvalues to stable locations, Multivariable frequency response plots were used by Hughes and Hamdan [4,5] for analysis and design of PSS. These methods help to determine the nature of phase lead compensation needed for stabilisation purposes. However these methods are applicable only to single machine equivalent models of the system and are not general enough to be used for the multimachine case.

Among the methods based on modern control theory there are mainly two approaches available, 1) those based on linear optimal regulator theory and 2) those based on pole - placement techniques.

In the approaches based on linear regulator theory [6-8], the stabilizer is designed as an optimal state feedback controller which minimizes a quadratic performance index.

The resulting controllers in these methods [6-8] improve the closed loop system performance, but the inaccessibility of all the states for feedback creates a problem in practical applications. Suboptimal controllers with the system represented by lower order models with only measurable states as state variables have been developed [9]. The resulting controllers are optimal only with respect to the model considered. Davison and Rao [10] developed a design method for PSS using output feedback by minimizing an average performance index as proposed by Athans and Levine [11]. De Sarkar and D. Rao [12] designed excitation control for stabilizing a synchronous machine through output feedback by first considering state feedback obtained through application of optimal control theory and then getting a 'minimum norm' suboptimal control law for output feedback . The weighing matrices and the output variables are chosen to improve both small and large signal machine responses.

Lately, there has been interest in the application of pole assignment techniques to the problem of power system stabilization [13-20]. This approach provides a design method for the PSS with the control objective of assigning the closed loop eigenvalues to specified stable locations. Among this class of methods, there are two basic divisions namely, i) methods using state feedback and ii) methods using output feedfack.

The basic principle of pole assignment techniques for PSS is shifting the open loop eigenvalues to desired locations by auxiliary feedback. If the system is controllable, all the open loop eigenvalues can be shifted to arbitrary locations with state feedback provided complex eigenvalues exist in conjugate pairs. If the system is not fully controllable, the eigenvalues associated with the controllable modes can be shifted arbitrarily if the complex eigenvalues exist in conjugate pairs, by state feedback. In the literature there are many pole assignment techniques available with state feedback [13-16]. Out of these, Ref. [14,15] offer simple technique using modal control theory. However, unavailability of all the states for feedback always poses a practical problem for these methods.

From a practical viewpoint pole assignment using output feedback is more important. If the system is completely controllable and observable then all its modes can be shifted by output feedback provided the complex eigenvalues exist in conjugate pair [21]. Most of the literature available has considered PSS design as a problem of designing dynamic output feedback [22-27] compensator. The number of poles that can be assigned depends upon the order of PSS. Usually a second order PSS is designed to assign the dominant eigenvalues of the system.

From the literature [17-20] it is observed that min.[n,m+l-1] poles of a completely controllable and observable

system can be assigned to desired location by gain output feedback , where n represents the system order, m and l represents number of inputs and outputs of the system respectively. Padiyar et al. [22] have presented three methods for the design of PSS by pole assignment with output feedback. The first method is based on modal control theory. The second and third methods involve static optimization for exact assignment of poles and assignment into a sector. Arcidiacono et al. [23] proposed a technique for PSS design which utilizes the residues of open-loop transfer function to get a specified set of closed-loop eigenvalues. Fleming et al. [24] designed a sequential algorithm for tuning the parameters of PSS with fixed poles in multimachine power system. Sequential addition of stabilizers disturbs previously assigned eigenvalues and hence may not give satisfactory performance in many cases. Lefebvre [25] proposed an algorithm for simultaneously tuning of all the PSS in a multimachine system. Abe and Doi [26,27] developed a design technique by combining the frequency response and pole assignment methods. Munro and Hirbod [31] presented a very systematic design of full rank output feedback controllers which allow arbitrary pole assignment in the closed-loop system. Lefebvre [33] has recently used the tuning of PSS in three machine system. Here, firstly the design are done for completely decoupled system, then the PSS parameters are updated as the interconnection is slowly introduced.

1.5.2 Adaptive PSS Design

So far, the PSS design techniques discussed were for design at a particular operating point to provide the necessary damping torque. However, the operating point is not fixed. It keeps changing with change in loading conditions and the performance of the stabilizers, under changed operating condition are not always satisfactory. This is why the need for adaptation has been felt. Adaptive stabilizer design to enhance both dynamic and transient stability has been developed by Ghosh [28]. Here the controllers developed are based on recursive parameter estimation. For this the recursive least squares identification scheme was used. Also the proposed adaptive stabilizers have been implemented on a 16 bit microprocessor. The availability of low cost microprocessor chips has made it possible to design adaptive PSS. The use of digital adaptive regulators, called self tuning regulators, for power system stabilization has been reported in the literature [29,30].

1.6 SCOPE FOR THE PRESENT WORK

It has been felt that non-adaptive PSS designs are not satisfactory under changing operating conditions. Also a fully adaptive design involves complexities in implementation. The design method proposed in the present thesis gives good performance under changing operating conditions. At the same time, it avoids the complexities involved in the traditional

adaptive design. The scheme proposed is general enough to be applicable for changing system configuration, (e.g., strong and weak systems). So,the designed controller will give satisfactory performance over a wide range of operating conditions and network parameters.

A chapterwise brief summary of the work done is presented below;

Chapter 2 considers a conventional non-adaptive PSS design using dynamic output feedback. The algorithm used was developed by Munro and Hirbod [31]. A single machine infinite bus system model is developed. The stabilization singal used is derived from angular velocity of generator rotor. Since we prefer to go for complete pole placement,the minimum order of PSS required is three. Design of such a PSS has been outlined, and its transfer function obtained.

Chapter 3 contains the proposed adaptive PSS design. Numerical results are obtained for a single machine infinite bus model, at different operating points. The time responses show the superiority of the proposed scheme over the conventional nonadaptive designs. Quality of performance of the proposed PSS with change in system strength is discussed.

In chapter 4 we have dealt with the adaptive PSS design for a multimachine system. A 3 machine, 9 bus system model is considered for the purpose. The proposed adaptive

PSS scheme is generalised enough from the earlier formulation for application in the multimachine case. The design of PSS for each machine, for a given operating condition in the system is done by following the procedure given in Ref. [1]. Numerical results are given at a few operating points, which indicates the advantage of the proposed scheme over the existing ones.

Chapter 5 containes the general conclusion.

CHAPTER 2

POWER SYSTEM STABILIZER DESIGN

2.1 INTRODUCTION

The important role played by PSS on overall system performance has already been stated in the previous chapter. In fact since 1966 a number of studies [35-39] clearly indicates the beneficial effects of PSS on damping out oscillations of small magnitude in systems provided with modern high gain and fast acting voltage regulators. In this chaper we demonstrate a simple PSS design using a linearized state-space model of a synchronous generator connected to an infinite bus through a transmission line. The power system model used here is taken from Ref. [34]. An algorithm is presented for design of PSS based on pole placement technique. Numerical results are also presented for a PSS designed at a particular operating point.

2.2 POWER SYSTEM MODEL

In the most simple case, the power system consists of a synchronous generator connected to an infinite bus through a transmission line. The system alongwith exciter-voltage regulator is shown in Fig. 2.1. The nonlinear system dynamics and linearized system equations derived from the nonlinear equations about an operating point are given in Appendix A-1.

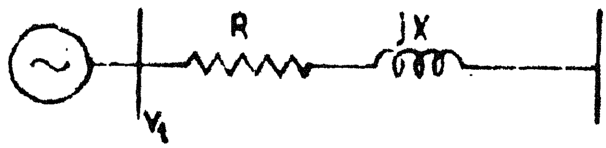

FIG. 2.1(a) System diagram

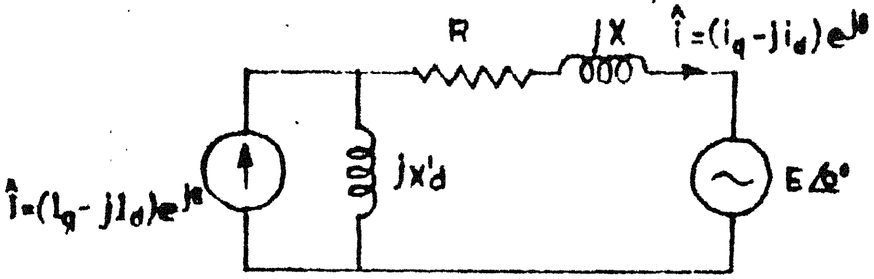

FIG. 2.1(b) Single phase equivalent circuit of the model

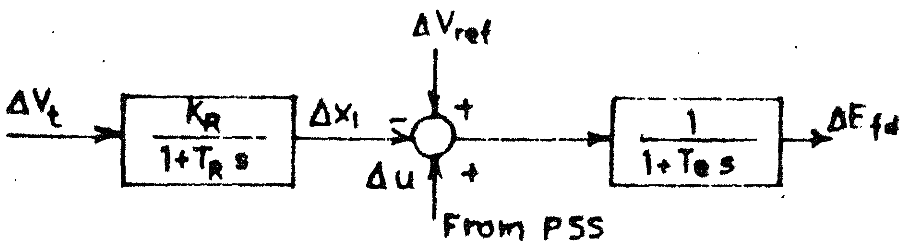

FIG. 2.1(c) Block diagram of excitation system

The linearized system equations for a typical operating point are given below. Derivation of this model and the system data used for this purpose are given in Appendix A-2.

The state and output equations are, respectively

$$\dot{\underline{x}} = A\underline{x} + Bv \qquad \text{.....(2.1)}$$

$$y = C\underline{x}$$

Where $\underline{x}^t = [\Delta I_d, \Delta\delta, \Delta\omega, \Delta X_1]$

$$v = [\Delta u] \qquad \text{.....(2.2)}$$

$$A = \begin{bmatrix} -0.16312 & -0.3278 & 0.0 & -0.34722 \\ 0.0 & 0.0 & 1.0 & 0.0 \\ -26.34 & -47.5885 & 0.0 & 0.0 \\ 719.0961 & -773.2739 & 0.0 & -100.0 \end{bmatrix} \qquad \text{...(2.3)}$$

and

$$B = \begin{bmatrix} 0.34722 \\ 0.0 \\ 0.0 \\ 0.0 \end{bmatrix} \qquad \text{......(2.4)}$$

For the present purpose of this work the feedback variable considered is angular velocity ($\Delta\omega$). Thus

$$y = [\Delta\omega] \qquad \text{.....(2.5)}$$

and $C = [0.0, 0.0, 1.0, 0.0]$

For the above mentioned case, complete pole placement is done. Eigenvalues of the system without PSS are given in Table (2.1). From the Table it is clear that the system is unstable. Our

prime objective in designing PSS is to stabilize the system by shifting the unstable dominant eigenvalues to a suitable location in the left half plane.

Sl.No.	Eigenvalues
1.	0.533+j 7.107182
2.	0.533-j 7.107182
3.	-3.734817
4.	-97.4773

Table 2.1 Eigenvalues of the power system without PSS.

2.3 PROBLEM FORMULATION

Let q be the number of poles to be placed and m and l be the number of inputs and outputs respectively. For our model given by eqns.(2.1-2.5), $n > m+l-1$, where n is the system order. The problem is to find an output feedback lqw

$$U(s) = -F(s).Y(s) \qquad \ldots.(2.6)$$

Where F(s) is a proper rational polynomial matrix of minimal order r, such that all the (n+r) poles of the composite system get placed at specified locations.

2.4 ALGORITHM AND RESULTS

Since in this study we use only one output as feedback variable, the transfer function matrix F(s) of the

compensator in equation (2.6) is a scalar function. For compensator order of r, its transfer function can be represented as:

$$F(s) = \frac{\beta_o s^r+\beta_1 s^{r-1}+\beta_2 s^{r-2}+ \ldots +\beta_r}{s^r+\alpha_1 s^{r-1}+\alpha_2 s^{r-2}+ \ldots\ldots +\alpha_r} \qquad \ldots (2.7)$$

Since we opt for complete pole placement, order of the compensator required is r=3 (Justification of this statement can be found in Ref. [45]. So in our case

$$F(s)= \frac{\beta_o s^3+\beta_1 s^2+\beta_2 s + \beta_3}{s^3+\alpha_1 s^2+\alpha_2 s+\alpha_3} \qquad \ldots (2.8)$$

The algorithm used for determining F(s) was developed by Munro and Hirbod [31] and is presented in Appendix A-3. No restrictions are placed on the parameters of F(s) in their determination. Table 2.2 gives the desired and assigned locations of closed loop poles as well as the parameters of the dynamic compensator which accomplishes the assignment.

2.5 DISCUSSION

It is observed from the results that all the pole locations in the closed loop system are in the left half of the s-plane. It is further observed that due to slight numerical inacuracies in computation, the pole locations are not exact, though there is no substantial deviation between the desired locations and the actual locations where the

Feedback variable	ω only
No. of poles to be placed	7 Note $n=4$ $r=3$ $n+r=7$
Desired location of closed loop poles	$-1.0+j\ 7.107182$ $-1.0-j\ 7.107182$ -97.47773 -3.734817 $-20.0,\ -15.0,\ -25.0$
Order of compensator	3
Compensator T.F.	$\dfrac{-3.7135s^3-392.5681s^2-3155.578s-6527.1}{s^3+62.31s^2+1290.97s+7573.24}$
Locations of assigned closed loop poles.	$-1.0+j\ 7.080849$ $-1.0-j\ 7.080849$ -97.47779 -3.731152 $-15.1418+j\ 5.560658$ $-15.1418-j\ 5.560658$ -28.87101

Table 2.2 Numerical results of complete pole placement.

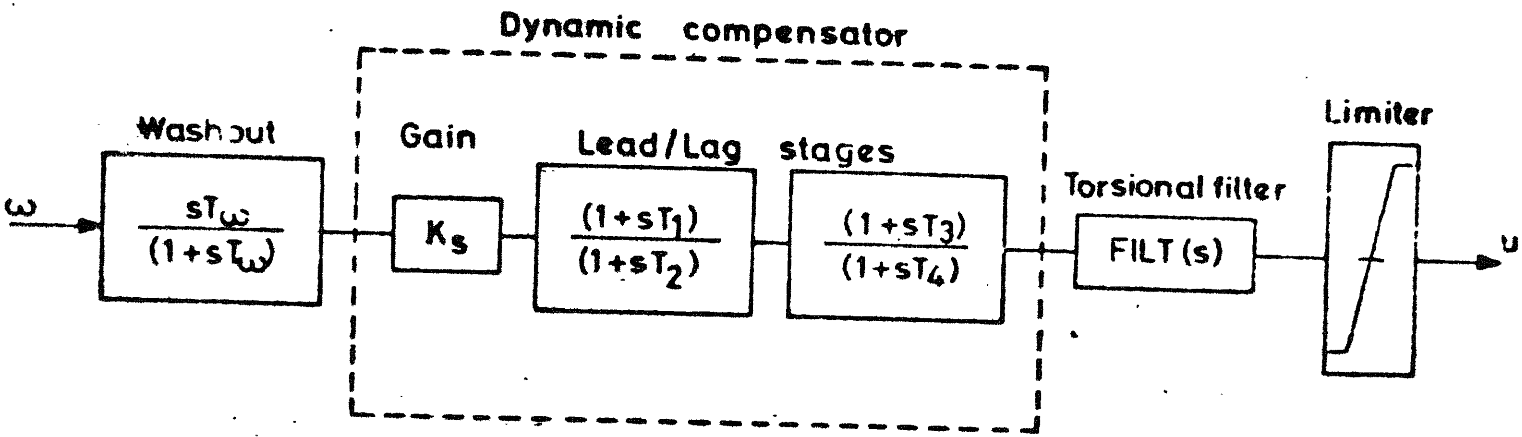

FIG 2.2 BLOCK DIAGRAM OF A PRACTICAL PSS.

poles got placed. The traditional design technique uses a lead/ lag-lead type of compensator [46] and conventionally the order is kept at 2 (Fig. 2.2). Stabilizing signals used are accelerating power, frequency and velocity. Here we choose only velocity feedback and we observed that a 3rd order compensator is better than the conventional 2nd order compensator, so we opted for 3rd order PSS. The addition of a third order compensator has increased the number of poles of the closed loop system by three. It is difficult to determine what should be the values specified for these three extra poles. They are specified to be real and negative with large magnitudes. The exact locations are specified rather arbitrarily. Two of these three poles have assumed complex conjugate locations and the remaining is real. All are stable. The algorithm is computationally efficient, also it determines the minimal order compensator, which is an advantage. In the literature, there are several other methods available [40-42] for the same purpose. However, we have chosen the simplest one. The same algorithm will be used in the next chapter for the purpose of developing an adaptive PSS for a wide range of operating conditions.

CHAPTER 3

ADAPTIVE PSS DESIGN FOR WIDE RANGE OF OPERATING CONDITIONS

3.1 INTRODUCTION

The PSS described in the previous chapter works satisfactorily so long as the system operating conditions do not change significantly. However, the system operating conditions do change significantly. It is shown in [2] that excitation system has conflicting effects on the synchronizing and damping torques as the operating conditions change. Under heavy loading conditions, the effect of excitation system is to increase the synchronizing torque in the system and reduce the damping torque. The reduction in damping torques, particularly in systems with long transmission lines, results in extremely oscillatory behaviour of the system. There is, thus, need for developing compensators which operate reasonably well over a range of operating conditions. Indeed the compensator should function well even when the system configuration changes due to faults or any other reason. One solution to this problem is a fully adaptable compensator, which, on identification of any change in the operating conditions as well as system configuration, changes the structure as well as parameters of the PSS. such adaptation processes would require computers for implementation. They should be reasonably fast for on line implementation. This method however, suffers from the drawback of high implementation

cost and complexity of system. So the search for simple adaptive schemes continues. In this work we describe one such method which might be a possible answer to the problem. It is to be kept in mind that more work needs to be done before it can be presented as a practical solution to the industry.

3.2 PROPOSITION

The method we present here is surprisingly simple from its physical point of view. Instead of having a single PSS, we have several PSS, each designed for a particular operating point. All the PSS are active simultaneously and each contributes to the AVR-exciter block through a weighting factor. Of this whole scheme, only the weighting factors are subject to change as the operating conditions change. A block diagram representation of the scheme is given in Fig. 3.1, which uses five individual PSS simultaneously, to generate a composite PSS.

3.3 IMPLEMENTATION

To carry out the work proposed in the previous section let us consider the space of operating conditions, with its two axes as real and reactive powers generated by the synchronous generator at any time. Since real and reactive powers supplied are governed by the load condition, the operating point moves in this space. We select five typical operating points placed symmetrically over the full load

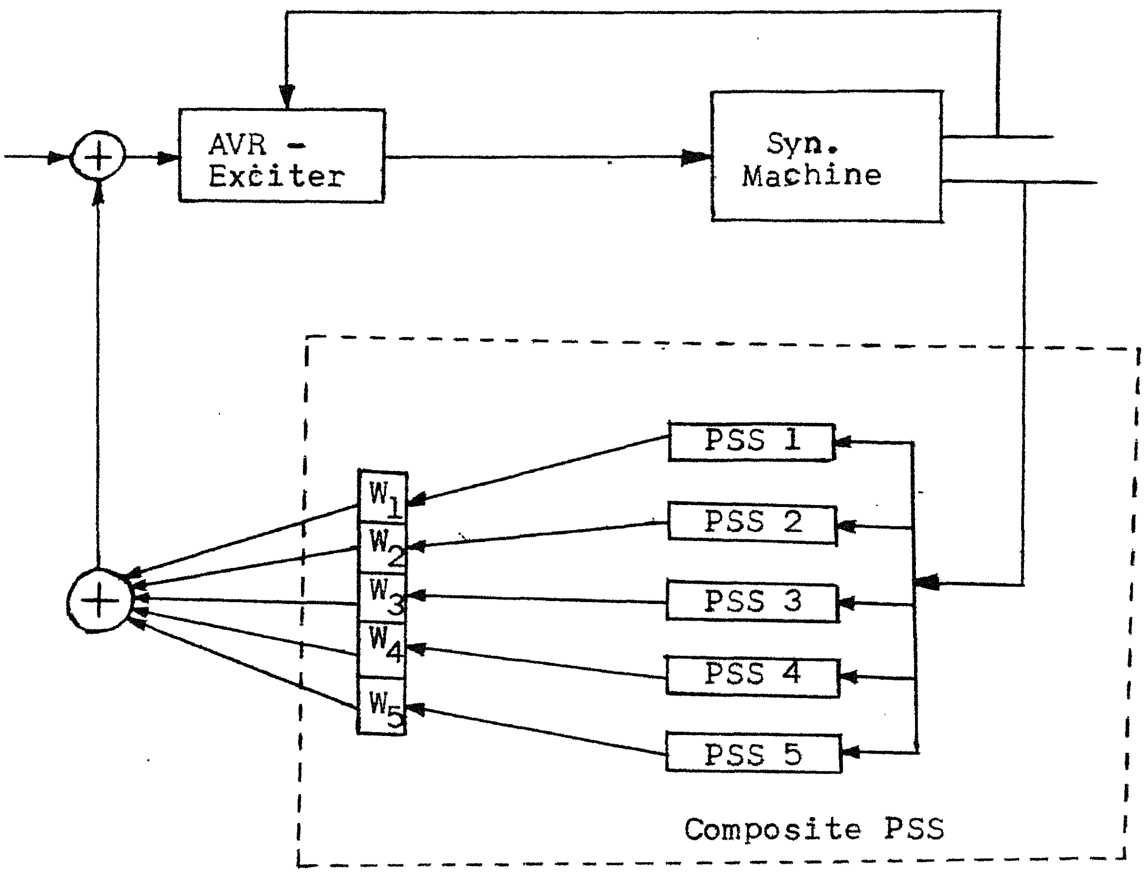

Fig. 3.1 An Adaptive Composite PSS Scheme.

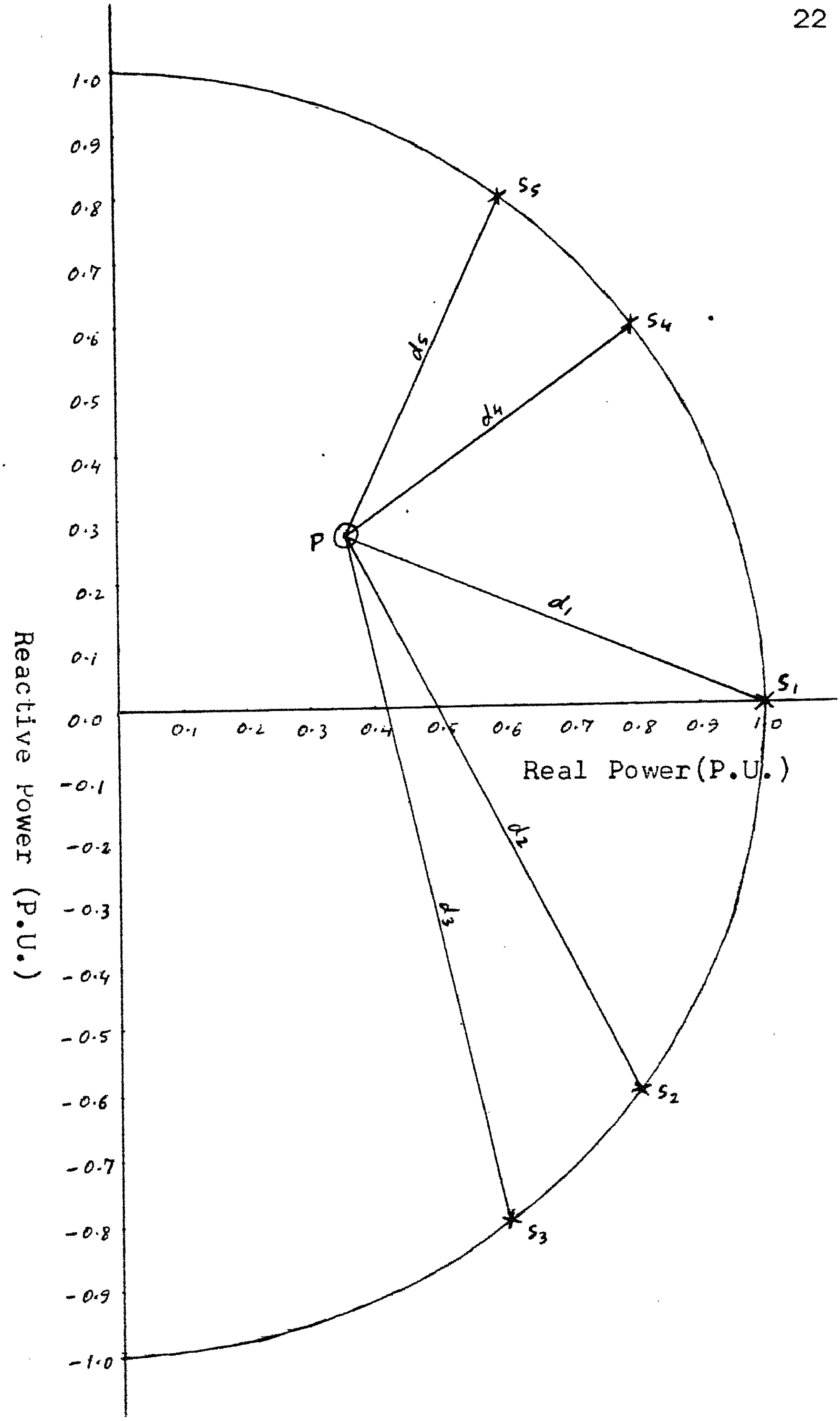

Fig. 3.2 Operating Space With Five Design Points.

curve which covers a range of power factors from 0.6 (lag)to 0.6 (lead), Fig. (3.2). It is unlikely that a practical system will be required to operate outside this range. Now for each of the five operating points considered, we assume that there is only one PSS. We design the PSS using the algorithm presented in the last chapter, so that all the closed loop poles are assigned fairly close to the desired locations in the left half plane. Thus we design five PSS for the five distinct operating points considered. Note that the system matrix [A] changes with change in real power (P) and reactive power (Q) flow . However, since the number of inputs to the PSS (in this case ω only) and the number of poles to be assigned does not change, the structure of the compensator remains unchanged and only its parameters change. The transfer functions for these five PSS are as shown in Table 3.1. At any instant the weighted sum of the outputs of these five PSS is fed into the AVR-exciter block. A simple procedure to determine the weightages is presented in the next section.

3.4 WEIGHTAGES FOR PSS

It is now necessary to develop a scheme for calculating the weightages to be used in the composite PSS shown in Fig. 3.1. The scheme should be fast and effective. A simple scheme for this purpose is proposed below.

T.F.1	$\dfrac{\beta_{o1}s^3+\beta_{11}s^2+\beta_{21}s+\beta_{31}}{s^3+\alpha_{11}s^2+\alpha_{21}s+\alpha_{31}}$
T.F.2	$\dfrac{\beta_{o2}s^3+\beta_{12}s^2+\beta_{22}s+\beta_{32}}{s^3+\alpha_{12}s^2+\alpha_{22}s+\alpha_{32}}$
T.F.3	$\dfrac{\beta_{o3}s^3+\beta_{13}s^2+\beta_{23}s+\beta_{33}}{s^3+\alpha_{13}s^2+\alpha_{23}s+\alpha_{33}}$
T.F.4	$\dfrac{\beta_{o4}s^3+\beta_{14}s^2+\beta_{24}s+\beta_{34}}{s^3+\alpha_{14}s^2+\alpha_{24}s+\alpha_{34}}$
T.F.5	$\dfrac{\beta_{o5}s^3+\beta_{15}s^2+\beta_{25}s+\beta_{35}}{s^3+\alpha_{15}s^2+\alpha_{25}s+\alpha_{35}}$

Table 3.1 Transfer functions of five PSS.

In the design space i.e. the space of operating conditions, there are five points at which we have already designed PSS. Let us call those five points as design points. Now while in operation, we locate the operating point at any time in the design space and calculate its linear distances from the five design points. Then we assign the individual PSS weightages in the ratio of the reciprocals of the distances of the operating points for which these PSS are designed from the operating point currently obtained , such that the sum of the five weightages is unity. Thus if the new operating point is such that it is at distances $d_1, d_2, \ldots, d_5$ from the operating points corresponding to the five stabilizers, PSS1, PSS2, ..., PSS5 respectively, then the respective weightages $w_1, w_2, \ldots, w_5$ are such that

$$w_1 : w_2 : w_3 : w_4 : w_5 = \frac{1}{d_1} : \frac{1}{d_2} : \frac{1}{d_3} : \frac{1}{d_4} : \frac{1}{d_5} \qquad \ldots\ldots(3.1)$$

Furthermore, $w_i \geq 0$, $i=1,2,\ldots,5$ and $\sum_{i=1}^{5} w_i = 1$

The logic behind such a procedure is simple. Thus, further away a new operating point is from a particular design point in the design space, less is the contribution of that design point towards determining parameters of the composite PSS for the operating point.

A Numerical Example

The five design points can be written, in terms of coordinates (P,Q), as

$s_1=(1.0,0.0)$, $s_2=(0.8,0.6)$, $s_3=(0.6,0.8)$, $s_4=(0.8,-0.6)$,
$s_5=(0.6,-0.8)$. ....(3.2)

Let the new operating point be located at (0.4, 0.7). The linear distances of the five design points from this new point in the design space are

$d_1=0.9219544$, $d_2=0.4123106$, $d_3=0.2236068$, $d_4=1.360147$,
$d_5=1.513275$. ....(3.3)

So, weightages given to the design points are in the ratio

$$w_1:w_2:w_3:w_4:w_5: = \frac{1}{d_1} : \frac{1}{d_2} : \frac{1}{d_3} : \frac{1}{d_4} : \frac{1}{d_5}$$

$= 1.085: 2.425: 4.472:0.735:0.661.$ .....(3.4)

and $w_1+w_2+w_3+w_4+w_5 = 1$ ...

Thus the weightages for the PSS can be determined to be

$w_1=0.1157$, $w_2=0.2586$, $w_3=0.4768$, $w_4=0.0784$, $w_5=0.0705$ .... (3.5)

3.5 COMMENTS

The algorithm used for calculating weightages lacks sophistication in the sense that all it cares about is the linear distance in the P-Q plane. It does not discriminate between a deviation in real power and a deviation in reactive power. However, the simplicity of the procedure and negligibly small computing time required for calculating the weightages is a notable benefit. We have, of course, to check that this scheme gives satisfactory results. The fact that we have taken the sum of five weightages to be equal to unity is

justified because if by any chance, the new operating point happens to coincide with any one of the design points then we prefer to use only the PSS designed for that design point. Note that in such a case the weight corresponding to that design point will be unity, while all other weightages become zero. Also we have assumed that the weightages cannot be negative.

3.6 A PROBLEM ENCOUNTERED

Apparently the proposition made for having five PSS is a very simple one and it should not create any difficulty in designing. However, while working with this idea, we encountered what may be called a dimensionality problem. This is explained below.

We have considered a simplified linearized model of the power system. This model is of fourth order, and includes the AVR-exciter assembly. Also we have five designed PSS, each of which is of third order and each having distinctly different ploes and zeros. So, in general, at any operating condition the order of the combined closed loop system will be 4+3x5 =19, which is rather high. Analysis of the combined closed loop system is necessary to ensure that the system performance is satisfactory, and we would like to avoid problems of high order system if we can. So at this stage we decided to reduce the order of the closed loop system by reducing the order of the composite PSS even though this implied sacrificing some of the design freedom . These considerations become even more

important in multimachine system PSS design using the present approach. The technique used to tackle this problem is illustrated in the next section.

3.7 A SOLUTION TO THE PROBLEM OF DIMENSIONALITY

In order to reduce the order of the closed loop system we decided to specify identical denominators for the five PSS, so that all the five compensator poles are at the same locations. This would imply that we have to do partial pole placement in the design. Though in our previous design technique both the parameters of numerator and denominator polynomials were determined for acheiving the assignment of the closed loop poles, it has been observed [43-44] that the contribution of compensator poles to the final assignment of the closed loop poles of the system is not as significant as that due to compensator zeros. Thus the design freedom sacrificed is not much. So, we adopted the technique and prespecified all the denominator parameters of the compensator. For doing so a minor change was necessary in the program which was used for earlier design. Following this new algorithm we designed five PSS for the five design points and repeated the procedure described earlier in this chapter to decide about the weightages. The new PSS transfer functions for the five design points considered are given in Table 3.2. Here,as it

T.F.1	$\frac{-3.26s^3-336.78s^2-2039.89s-3151.04}{s^3+62.31s^2+1290.97s+7573.24}$
T.F.2	$\frac{-3171s^3-392.57s^2-3155.58s-6527.13}{s^3+62.31s^2+1290.97s+7573.24}$
T.F.3	$\frac{-5.28s^3-553.86s^2-4530.18s-9848.41}{s^3+62.31s^2+1290.97s+7573.24}$
T.F.4	$\frac{2.68s^3-467.68s^2-416.29s-9463.23}{s^3+62.31s^2+1290.97\ s+7573.24}$
T.F.5	$\frac{-6.20s^3-615.14s^2-1848.29s-4487.30}{s^3+62.31s^2+1290.97s+7573.24}$

Table 3.2 Transfer functions of five PSS with numerical values of parameters.

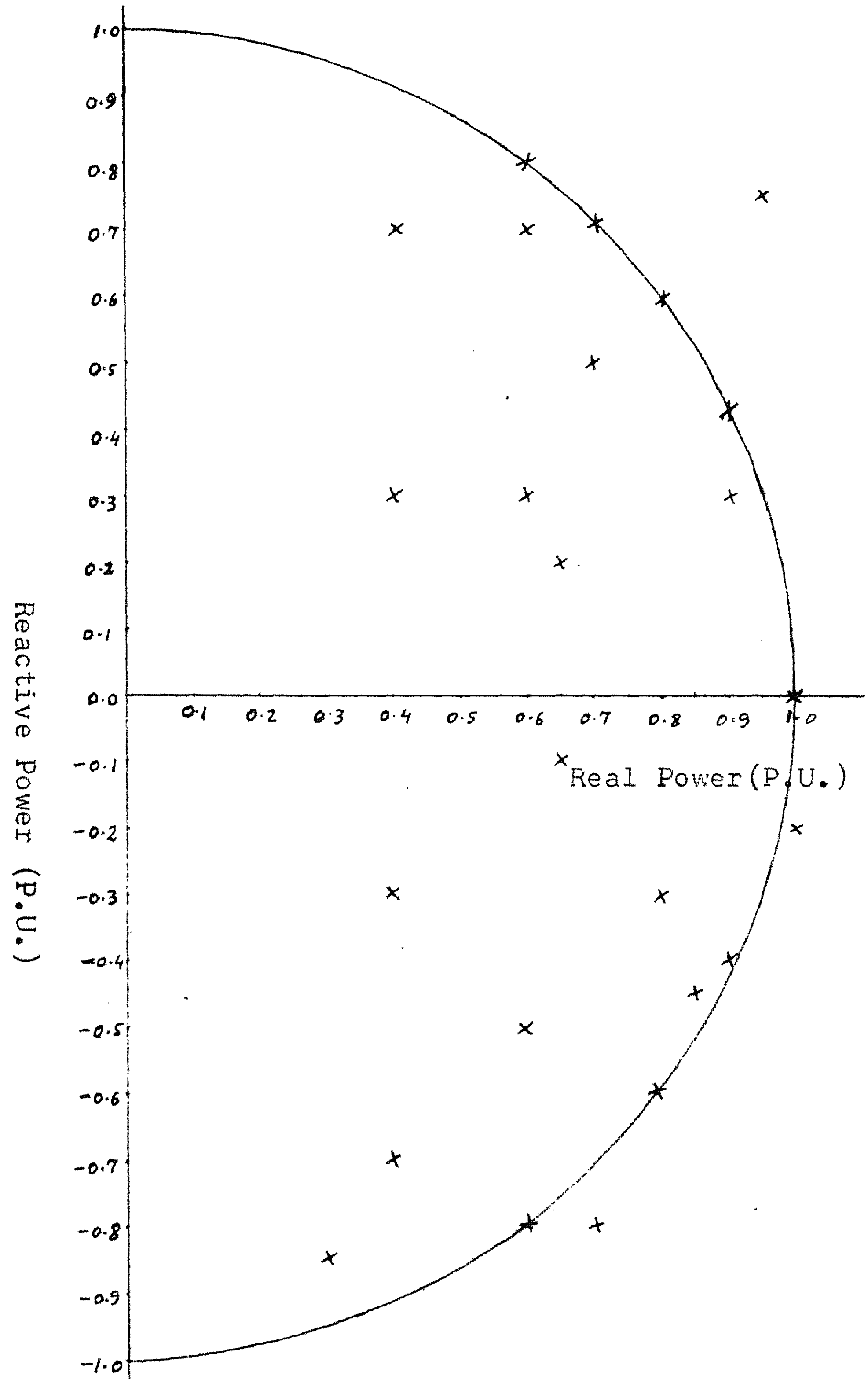

Fig. 3.3 Operating Space With Test Points.

is obvious from Table 3.2, we have decided to retain the poles of PSS 1 and fixed the pole locations of all other PSS to coincide with those of PSS 1. PSS 1 is designed using complete design freedom. This way of specifying the denominators of the PSS transfer functions is convenient and has a rationale.

In this way our aim to reduce the order of the closed loop system has been acheived, Now, for any new operating point, we have the closed loop system of order 4+3 = 7 which is significantly lower than the order of 19 in the case of full design freedom.

3.8 NUMERICAL RESULTS

We have tested the proposedalgorithm at 25 test points all over the design space, Fig. 3.3 . The results obtained at every point were satisfactory. In Table 3.3 we show some of the typical results obtained while testing the program, based on this algorithm, on a DEC- 1090 computer system.

From the results in the tabular form, the advantage of having the composite PSS comprising of the five individual PSS is not very apperant. To realize how superior the new algorithm is, we have to analyse the closed loop system with only one PSS (say PSS 1) at any test point in comparison with the composite PSS at the same test point. We performed this analysis with 3 kinds of arrangements:

Test Points	P=0.6 , Q=-0.5	P=0.65, Q=-1.0	P=0.65 , Q=0.2	P=0.9, Q=0.436
Pole locations of open loop system without PSS	-96.891, - 3.324033 0.0259287+j11.65919 0.0259287-j11.65919	-96.962 - 3.311335 0.055108+j10.0301 0.055108-j10.0301	-97.10267 -3.266139 0.1028419+j8.771972 0.1028419-j8.771972	-97.26561 -3.612487 0.3574926+j8.008154 0.3574926-j8.008154
Desired Closed loop pole locations	-96.891 -3. 324033 -1.0+j11.65919 -1.0-j11.65919 -20.0,-15.0,-25.0	-96.962 -3.3111335 -1.0+j10.0301 -1.0-j10.0301 -20.0,-15.0,-25.0	-97.10267 -3.266139 -1.0+j8.771972 -1.0-j8.771972 -20.0,-15.0,-25.0	-97.26561 -3.612487 -1.0+j8.008154 -1.0-j8.008154 -20.0,-15.0,-25.0
WEIGHTS w_1	0.1416	0.3197	0.2848	0.1977
w_2	0.0811	0.1625	0.2688	0.4604
w_3	0.0697	0.1291	0.1907	0.1875
w_4	0.4054	0.2229	0.1411	0.0850
w_5	0.3022	0.1658	0.1147	0.0695
Assigned closed loop poles	-96.8828 -3.314016 -0.91897+j11.91367 -0.91897-j11.91367 -23.97175+j2.05249 -23.97175-j2.05249 -12.49477	-96.95594 -3.297208 -1.17962+j10.16496 -1.17962-j10.16496 -16.12445+j2.157017 -16.12445-j2.157017 -27.61183	-97.09812 -3.243209 -1.412779+j8.770063 -1.412779-j8.770063 -15.01318+j5.352822 -15.01318-j5.352822 -29.27988	-97.26252 -3.587136 -1.382395+j7.903105 -1.382395-j7.903105 -14.25759+j6.902193 -14.25759-j6.902193 -30.34352

Table 3.3 Testing of the system with the composite PSS at a few operating points.

i) Only PSS 1 operating.
ii) Only PSS 2 operating.
iii) Composite PSS operating.

The results are given for four different operating conditions, in the form of time response of the closed loop system, when a disturbance of fixed magnitude is applied at time instant of zero. The state variables ∂ (angular position and ω (angular velocity) are chosen for displaying the system response [Fig. 3.4-3.11].

3.9 STRONG AND WEAK SYSTEMS WITH THE COMPOSITE PSS

To study the system with change in system configuration, two cases are considered, namely, strong system and weak system. The results produced above were for a weak system, with transmission line reactance of 0.7 P.U. The system designed has been analysed for strong system also, with $X_T = 0.2$ P.U. Improved system performance was observed. It has also been observed that even in the case of a very weak link, with $X_T = 1.4$ P.U., the system remained stable and the performance was satisfactory. Table 3.4 justifies these statements.

3.10 COMMENTS AND DISCUSSION

From the time responses drawn, the superiority of the proposed scheme of composite PSS over the conventional scheme of a single PSS is clearly evident. With change in system operating conditions, disturbances in the system due

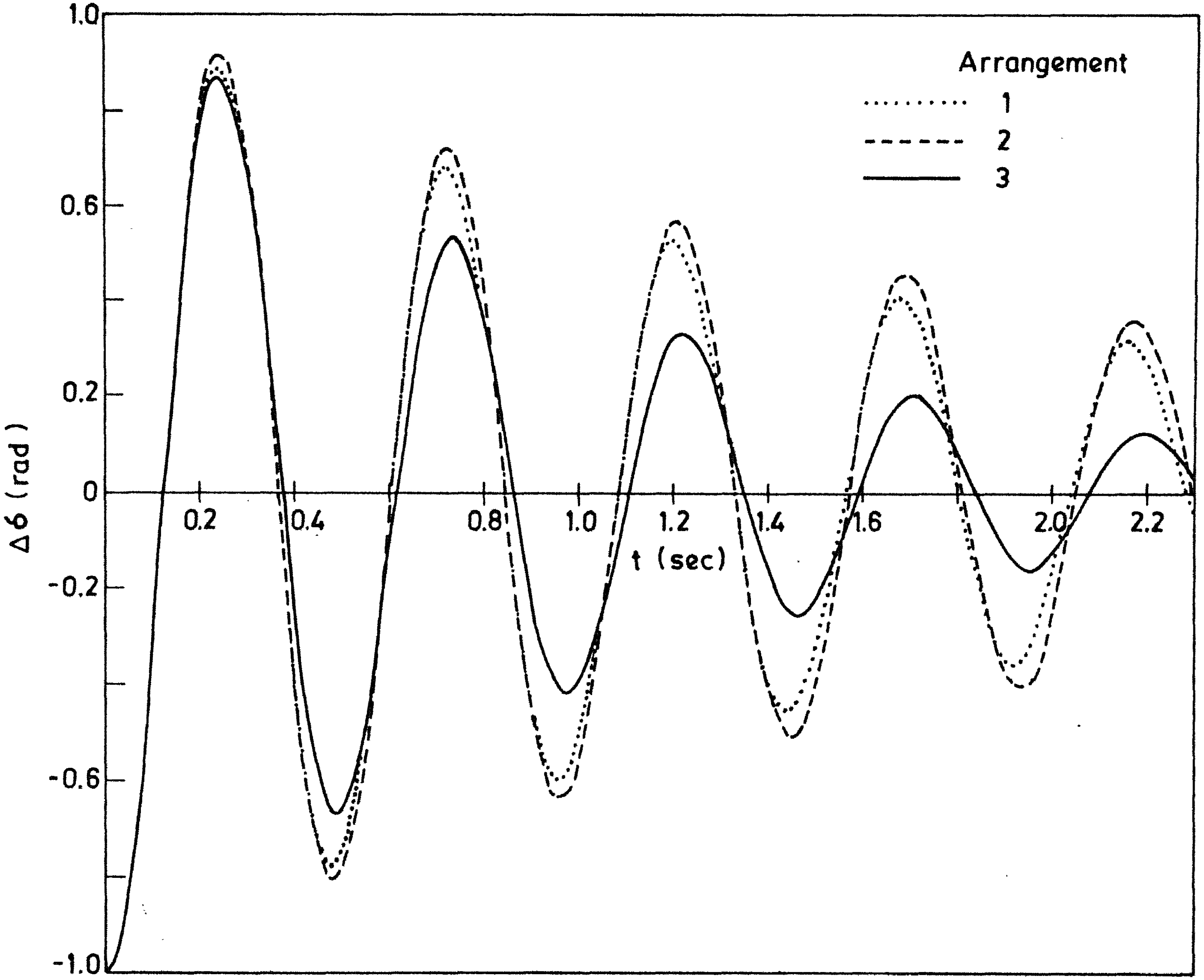

Fig. 3.4 Step response for rotor angle ($\Delta\delta$). Real power = 0.6 PU, Reactive power = -0.8 PU

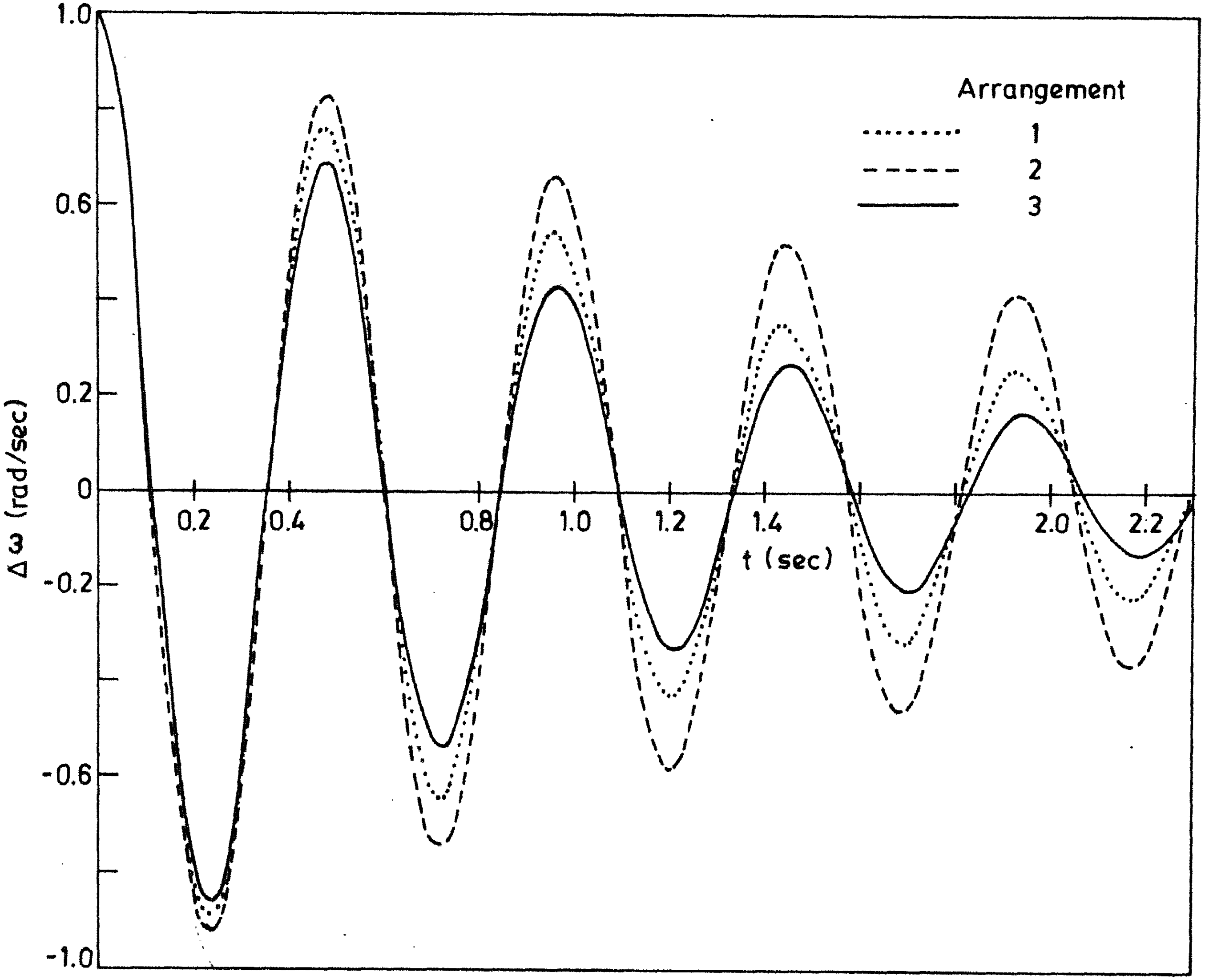

Fig. 3.5 Step response for angular velocity ($\Delta\omega$). Real power = 0.6 PU, Reactive power = -0.8 PU.

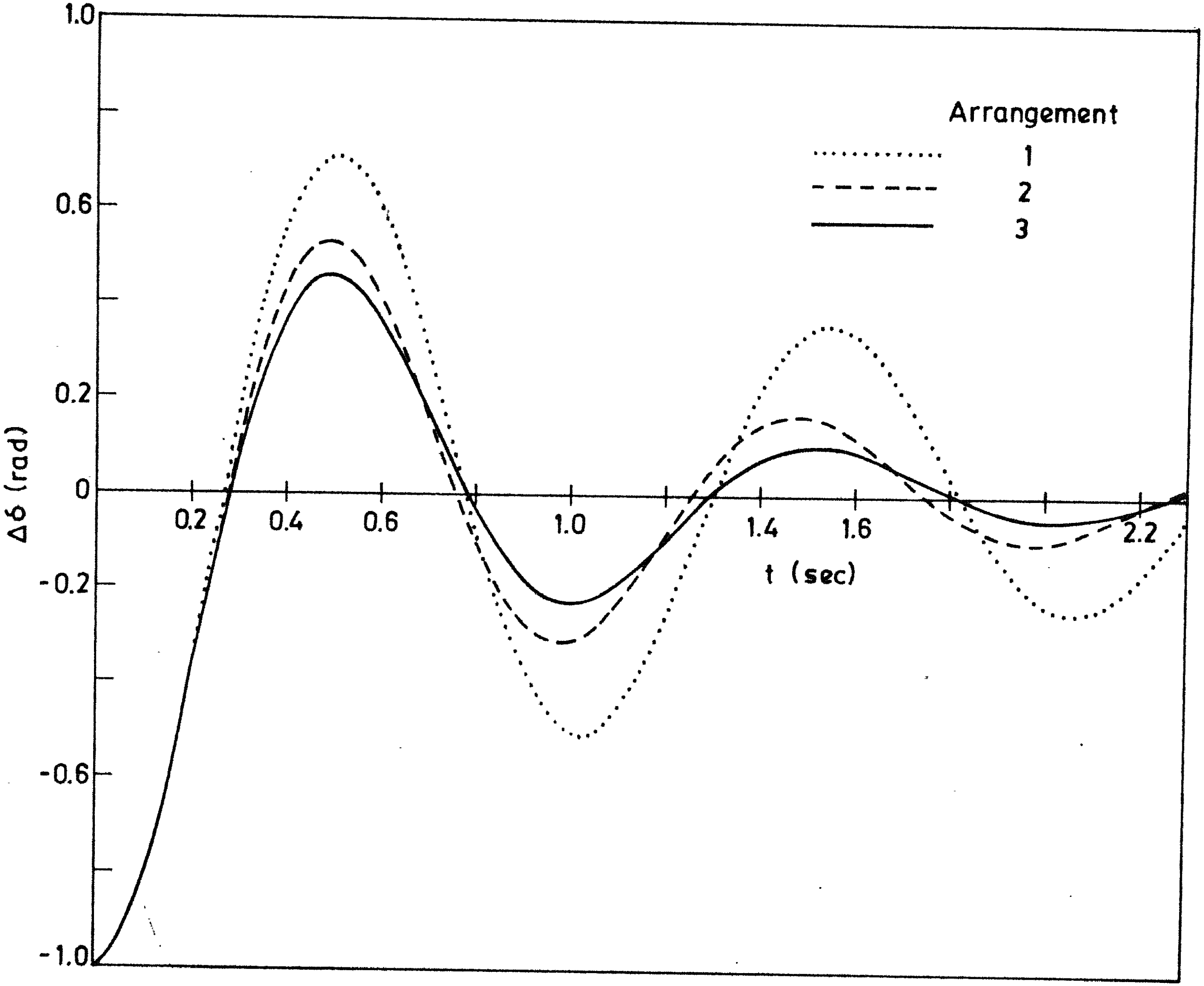

Fig. 3.6 Step response for rotor angle (Δδ). Real power = 0.4 PU , Reactive power = 0.7 PU

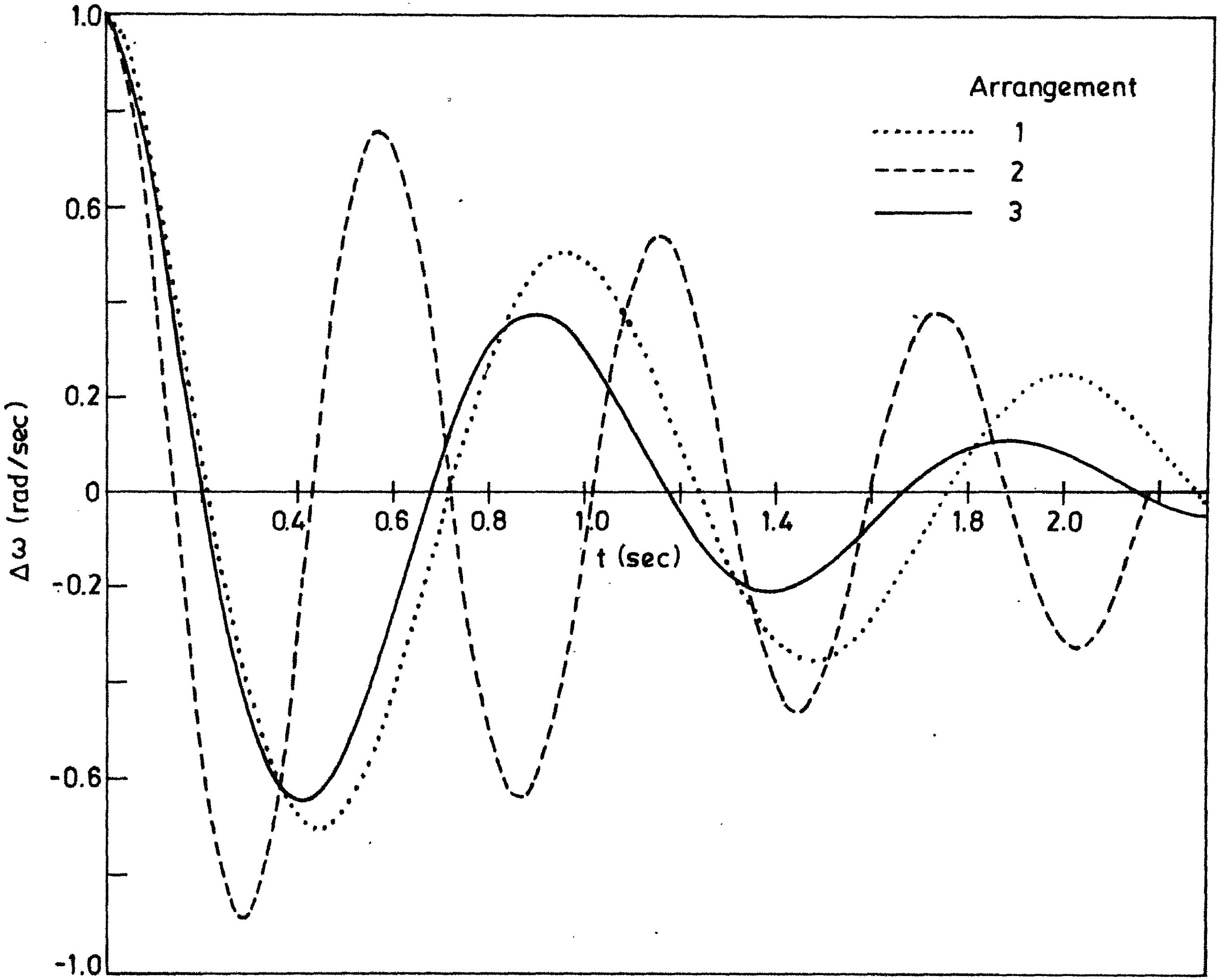

Fig. 3.7 Step response for angular velocity ($\Delta\omega$). Real power = 0.4 PU, Reactive power = 0.7 PU

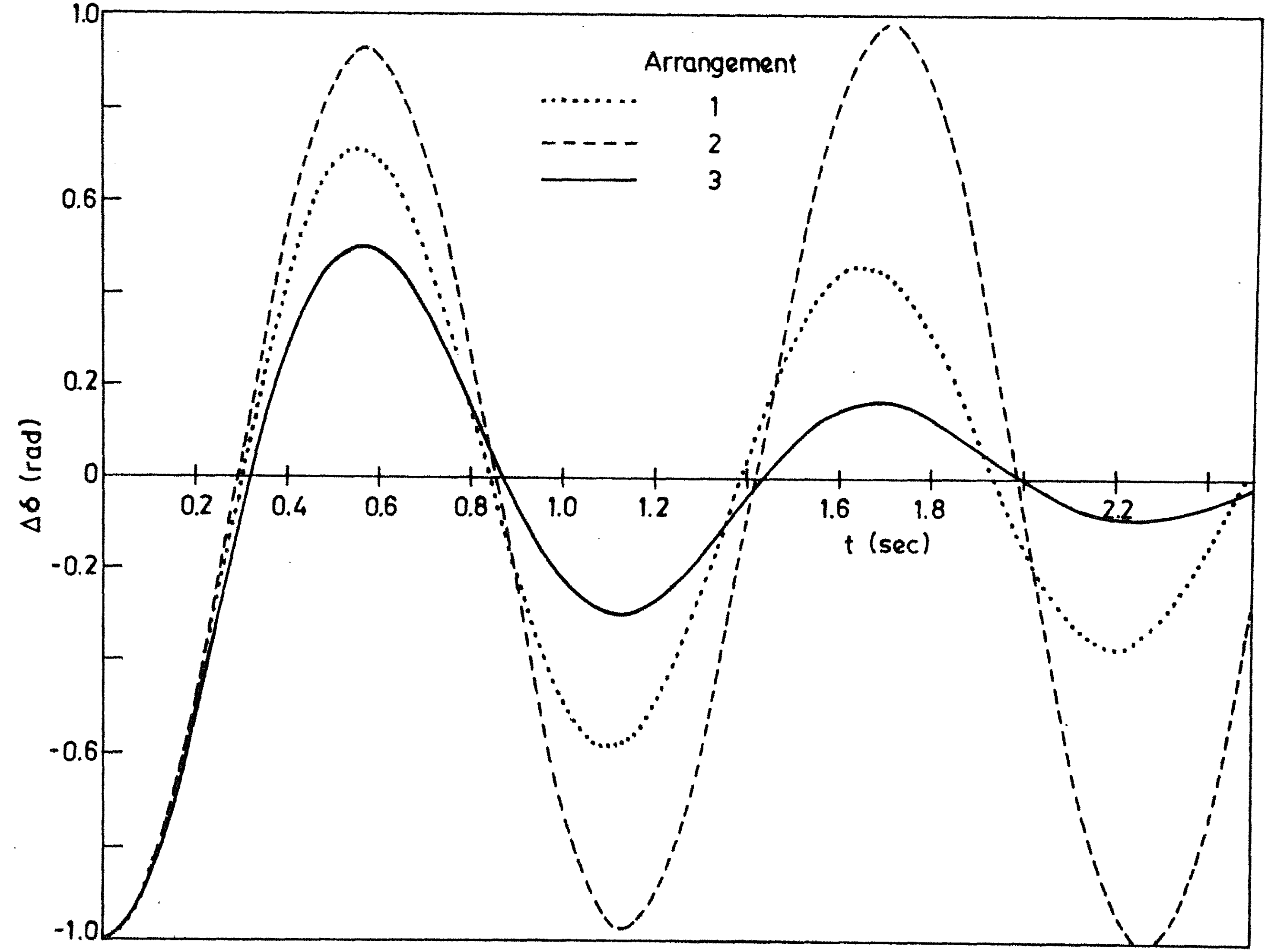

Fig. 3.8 Step response for rotor angle ($\Delta\delta$). Real power = 0.6 PU, Reactive power = 0.8 PU.

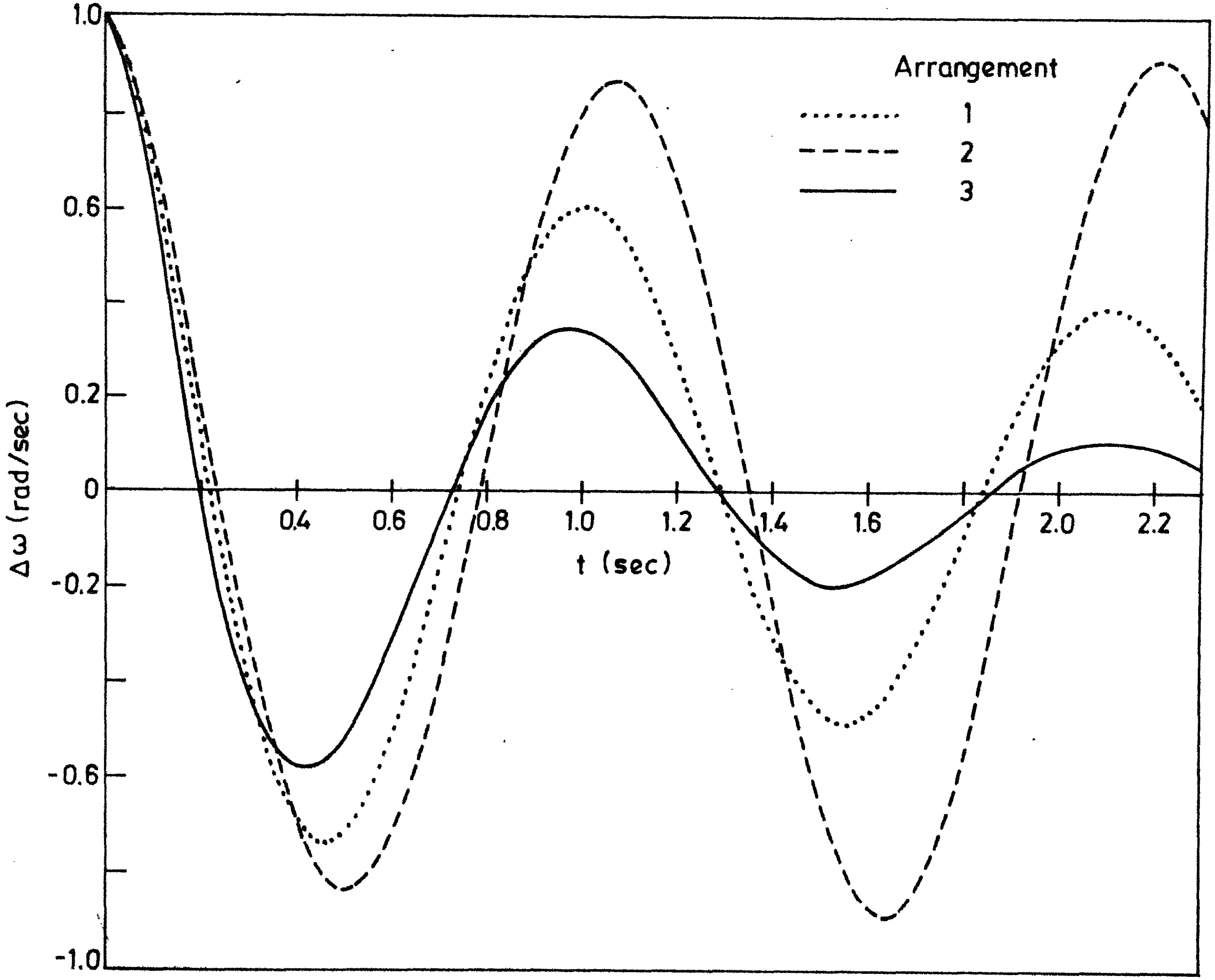

Fig. 3.9 Step response for angular velocity ($\Delta\omega$). Real power = 0.6 PU, Reactive power = 0.8 PU.

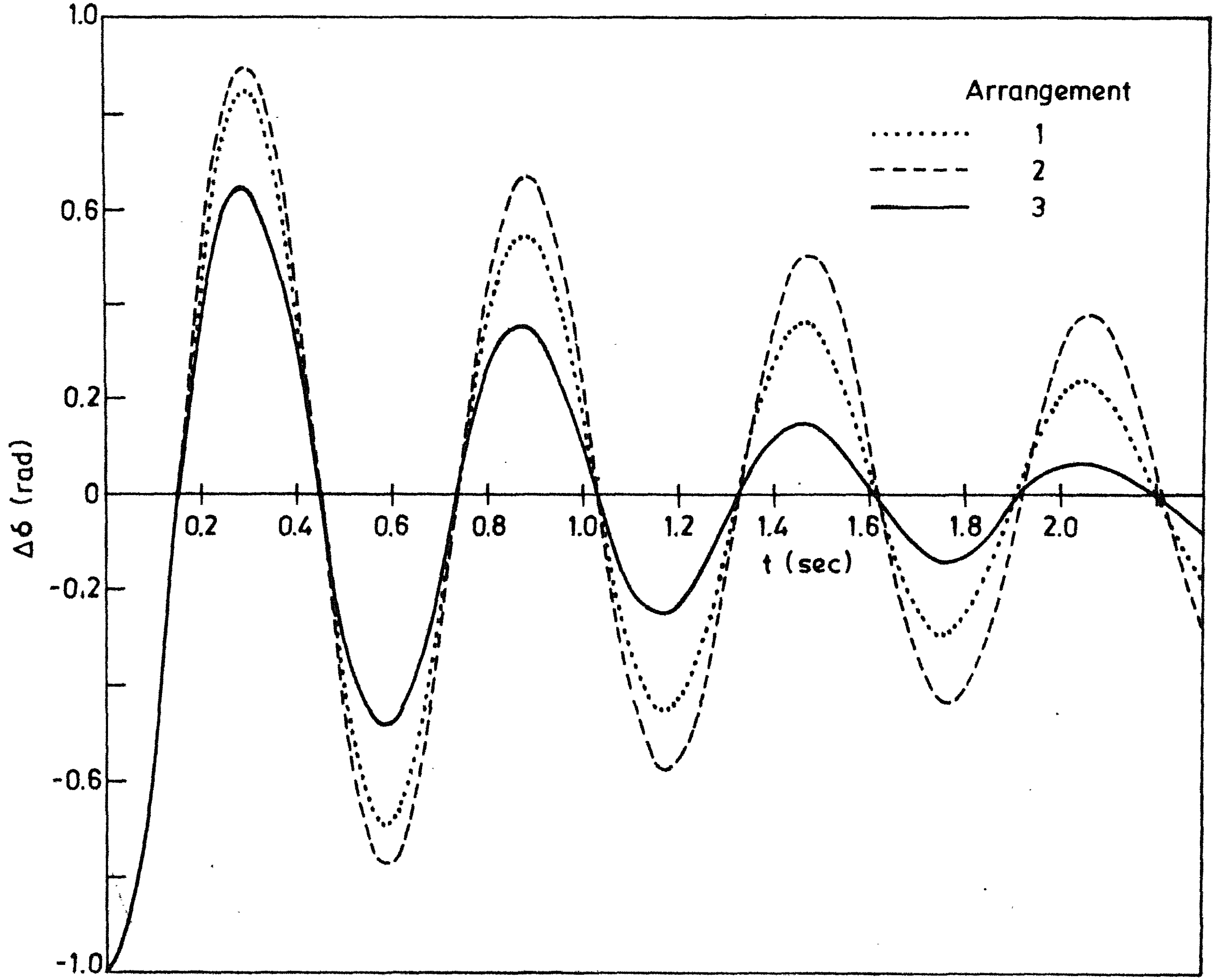

Fig. 3.10 Step response for rotor angle ($\Delta\delta$). Real power = 0.4 PU, Reactive power = -0.3 PU

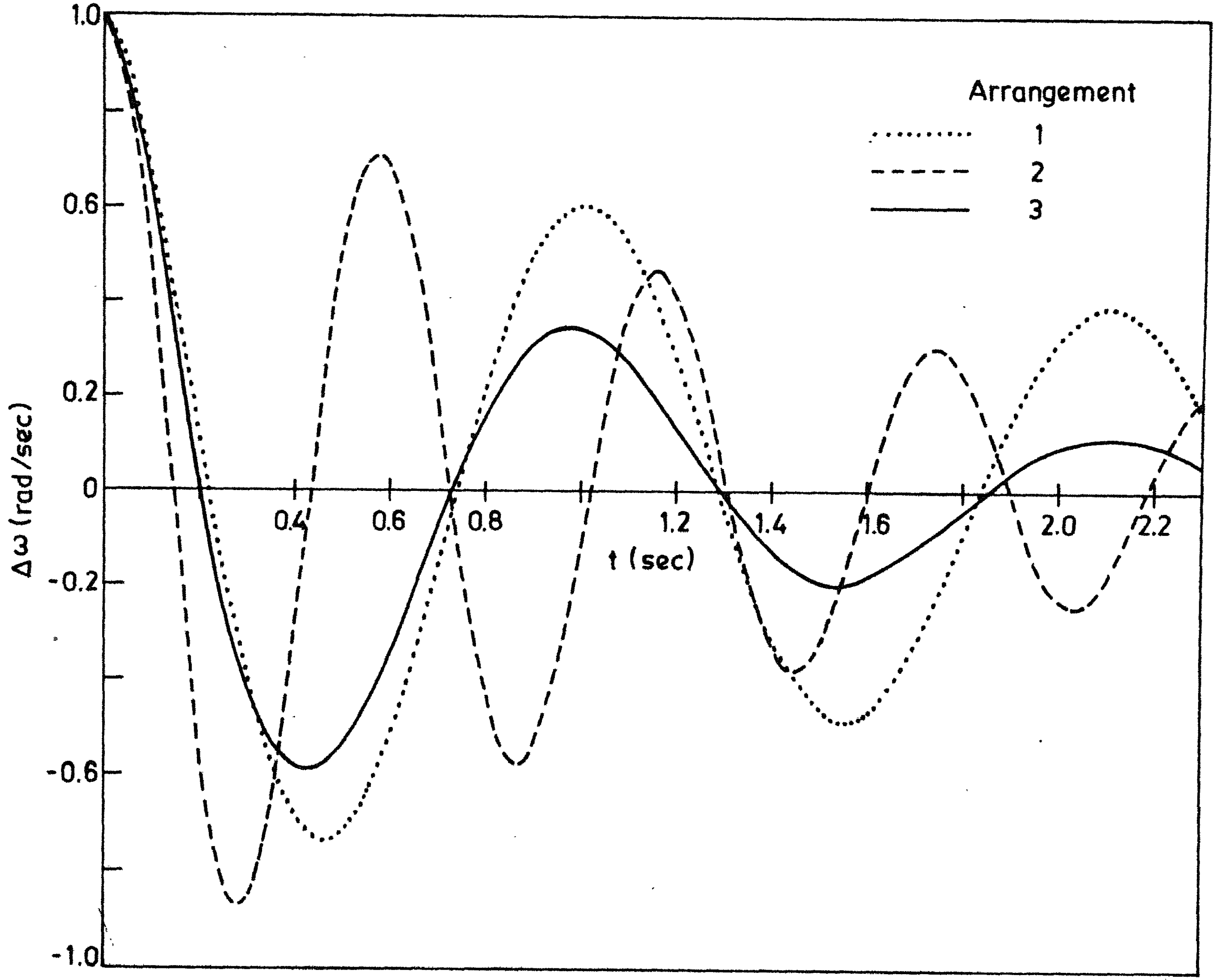

Fig. 3.11 Step response for angular velocity ($\Delta\omega$). Real power = 0.4 PU, Reactive power = -0.3 PU

SL. NO.	STRONG SYSTEM XT=0.2 PU	WEAK SYSTEM XT=0.7 PU	WEAKEST POSSIBLE SYSTEM XT=1.4 PU
1.	-98.1194+J0.0	-96.8668+J0.0	-96.3801+J0.0
2.	-24.4283+J3.8399	-25.0303+J6.5254	-25.39223+J7.5466
3.	-24.4283-J3.8399	-25.0303-J6.5254	-25.3922+J7.5466
4.	-11.5860+J0.0	-11.0743+J0.0	-10.7431+J0.0
5.	-2.1280+J0.0	-3.3106+J0.0	-3.7556+J0.0
6.	-0.9368+J14.6025	-0.5819+J12.4875	-0.3878+J11.2321
7.	-0.9368-J14.6025	-0.5819-J12.4875	-0.3878-J11.2321

TABLE 3.4(a) Strong and weak system eigenvalues for P=0.4 ; Q=-0.7

SL.NO.	STRONG SYSTEM XT=0.2 PU	WEAK SYSTEM XT=0.7 PU	WEAKEST POSSIBLE SYSTEM XT=1.4 PU
1.	-98.8090+J0.0	-98.1004+J0.0	-96.5992+J0.0
2.	-34.8304+J0.0	-31.4846+J0.0	-25.5801+J0.0
3.	-8.7663+J6.2282	-13.4431+J8.7516	-17.3152+J2.2303
4.	-8.7663-J6.2282	-13.4431-J8.7516	-17.3152-J2.2303
5.	-5.1979+J15.2837	-1.0178+J5.5946	-1.9155+J4.3353
6.	-5.1979-J15.2837	-1.0178-J5.5946	-1.9155-J4.3353
7.	-3.9664+J0.0	-1.7984+J0.0	-0.9858+J0.0

TABLE 3.4(b) Strong and weak system eigenvalues for P=0.6 ; Q=0.8

SL.NO.	STRONG SYSTEM XT=0.2 PU	WEAK SYSTEM XT=0.7 PU	WEAKEST POSSIBLE SYSTEM XT=1.4 PU
1.	-98.4631+J0.0	-98.2687+J0.0	-96.88115+J0.0
2.	-33.0985+J0.0	-31.1572+J0.0	-25.6652+J0.0
3.	-10.7238+J7.5025	-13.6870+J7.9556	-17.9696+J4.1931
4.	-10.7238-J7.5025	-13.6870-J7.9556	-17.9696-J4.1931
5.	-4.1729+J11.1294	-1.4975+J6.1695	-5.3200+J0.0
6.	-4.1729-J11.1294	-1.4975-J6.1695	-1.0332+J0.0
7.	-1.2089+J0.0	-2.6783+J0.0	-0.3336+J0.0

TABLE 3.4(c) Strong and weak system eigenvalues for P=0.4 ; Q=0.7

to changeover to a different set of weights will not be much It is ofcourse, possible to improve on the scheme proposed for selecting weightages or develop alternate schemes.

By prespecifying the poles of the compensator we have lost some of the design freedom and thereby the final locations of closed loop poles are affected slightly. However as it has been observed in Ref. [43], this kind of compensation is not very sensitive to the compensator pole locations. On the other hand, by doing so, we have acheived a great advantage of always having a stable compensator. If the denominator parameters of the compensator are free to assume any value then in some case it might generate a compensator with unstable poles. A stable system made by an unstable compensator [44] is undesirable. The question of the best choice of the composite compensator poles is a relevant and interesting problem. This, however, has not been investigated here.

Now questions may arise as to why we have chosen five PSS to make the composite PSS? What happens if more number of PSS are employed? Is there any limit on the number of PSS? The answer to these questions are not easy at the present moment; however,it may be attempted in the following way:

The performance of the system will no doubt improve with increase in the number of compensators. This is because with increase in the number of design points, the design space

is covered in greater detail. Also the choice of more appropriate design points will be an added factor which can be investigated. But the question of upper limit on the number of PSS must be approached from a more practical point of view. It makes sense to have as few PSS as possible in the composite PSS from the point of view of PSS hardware and/or software, as the case may be. We have found that five individual PSS give satisfactory system performance over a wide range of operating conditions. It is felt that the controller complexity has not been inordinately increased by this number of PSS.

CHAPTER 4

ADAPTIVE PSS FOR MULTIMACHINE SYSTEM

4.1 INTRODUCTION

So far we have applied our proposed algorithm for adaptive power system stabilisers only to a single machine infinite bus model. However, the systems we encounter in practice are multimachine systems. The design techniques used for single machine model cannot be used for multimachine system because of the effect of interconnection between different generating units in the latter case. Recently there has been much interest in coordinated application and design of PSS in multimachine power systems [50-52] . The design for multimachine PSS is constrained by the fact that only local signals are available for stabilization. The control to be used is, thus, decentralised control. It has been observed that all the machines in a multimachine system need not be equipped with PSS [1] . It is enough to provide PSS on a few selected units to ensure satisfactory system performance .

In decentralized control the entire system is divided into various subsystems, each having a local control station. Only local system outputs are used by controllers at each control station to control only local inputs. All the controller actions are of course, involved in controlling the

large system. Application of decentralised control has been recently done, by Lefebvre [33] using eigenvalue assignment, in a 3 machine system with PSS designed on all the machines.

In the literature, there are algorithms available, which consider sequential addition of stabilizers [32,2 using pole assignment technique. But the sequential additio of PSS disturbs the previously assigned eigenvalues. Simultaneous tuning of stabilisers as proposed in Ref. [33] is considered to be better alternative and used in this work.

In this chapter we described the system state and output equations for a typical, small, multimachine syste Coordinated design of PSS is carried out using the technique given in [25]. Two different schemes for determining the weightages to be applied for adaptive PSS design are presente Finally the numerical results are given at a few operating points to assess the adaptive PSS design. A schematic block diagram of the adaptive PSS scheme is shown in Fig. 4.1.

4.2 DESIGN PROCEDURE

To start with, we develop the non-adaptive design of PSS based on eigenvalue assignment, as in Anwar's thesis [Chapter -6, Ref.1]. We then consider the adaptive PSS design. Our design problem for non-adaptive PSS design can be stated as: Design PSS for all the machines in the multimachine system, with decentralised output feedback, to assign closed-loop eigenvalues to preassigned locations.

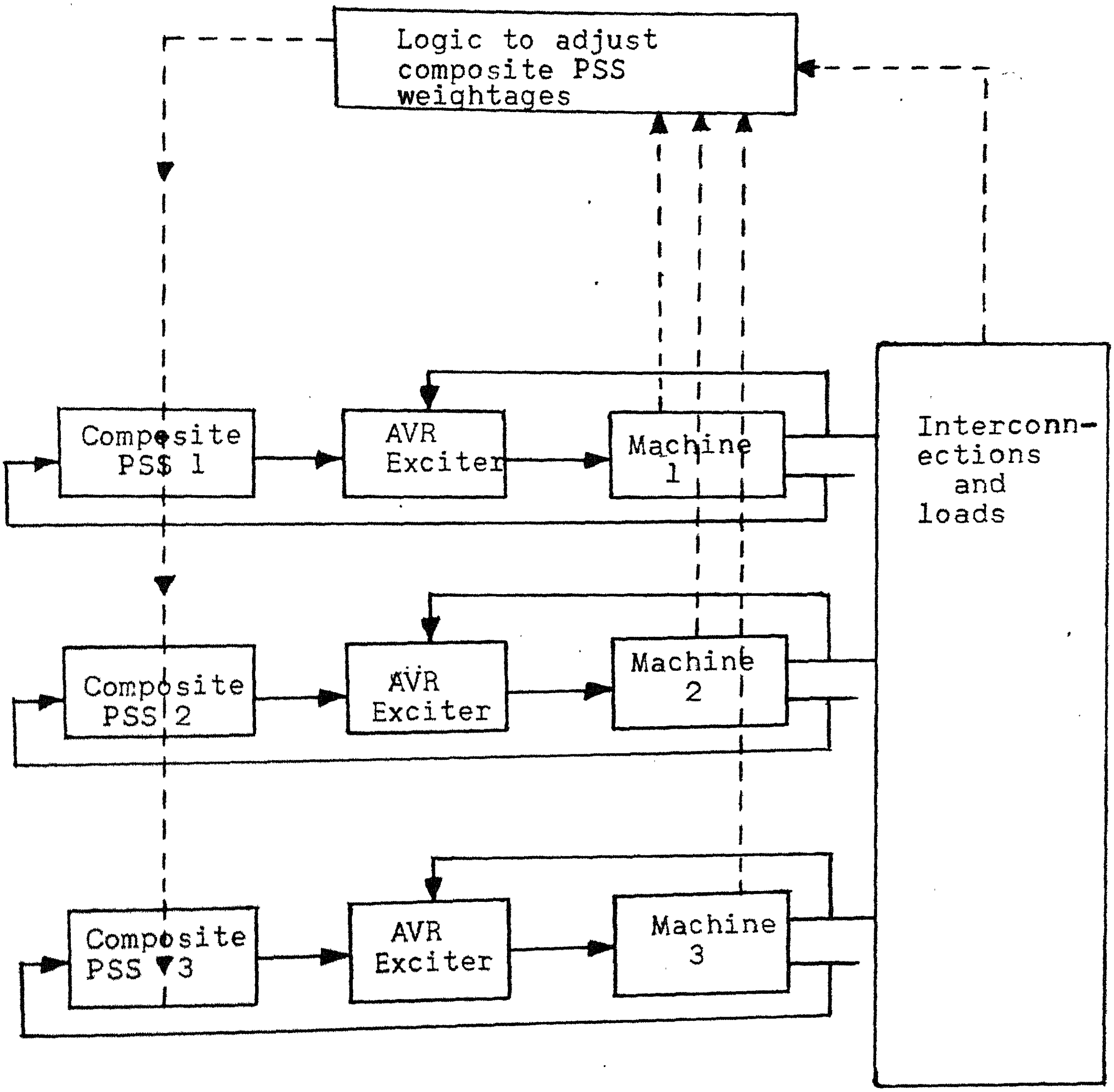

Fig. 4.1 Block diagram for Adaptive PSS in Multimachine Case.

4.3 FORMULATION OF CONTROL PROBLEM

The state space model of multimachine system with n generating units, developed in section 5.2 of Ref. [1] can be represented as

$$\dot{\underline{X}}_M = [A_M]\,\underline{X}_M + [B_M]\,\underline{U}_M \qquad \ldots.(4.1)$$

where,

$$\underline{X}_M = [\underline{x}^t_{m1}\ \underline{x}^t_{m2}\ \ldots..\ \underline{x}^t_{mn}]^t$$

and

$$\underline{U}_M = [u_{m1}\ u_{m2}\ \ldots..\ u_{mn}]^t$$

$\underline{x}_{mi}$ represents the state variables of ith generating unit and its excitation system. A_M is a full matrix and B_M is a block diagonal matrix, (see Sec. 5.2, Ref.[1]). The state equation of the ith generating unit can be written as

$$\dot{\underline{x}}_{mi} = [A_{mii}]\,\underline{x}_{mi} + \sum_{\substack{j=1\\ \neq i}}^{n} [A_{mij}]\,\underline{x}_{mj} + b_{mi}\,u_{mi} \qquad \ldots(4.2)$$

In eqn.(4.2), A_{mii} and A_{mij} are submatrices of A_M correspondin to the ith unit and b_{mi} is the ith diagonal block of B_M. Simil arly the output (eg. rotor speed) of the ith unit can be expressed as

$$Y_{mi} = [C_{mii}]\,\underline{x}_{mi} + \sum_{\substack{j=1\\ \neq i}}^{n} [C_{mij}]\,\underline{x}_{mj} \qquad \ldots.(4.3)$$

Since only decentralised control is considered, the second term in eqn. (4.3) can be dropped. The summation term in eqn. (4.2) represents the interconnection of the ith generati

unit with other units of the system. The interconnections are parameterized with $0 \leq r \leq 1$ as follows

$$\dot{\underline{x}}_{mi} = [\,A_{mii}\,]\,\underline{x}_{mi} + r\sum_{\substack{j=1\\ \neq i}}^{n} [A_{mij}]\,\underline{x}_{mj} + \underline{b}_{mi}\,u_{mi} \quad \ldots(4.4)$$

Eqn. (4.3) can be written, in view of decentralised control, as

$$Y_{mi} = [C_{mii}]\,\underline{x}_{mi} \quad \ldots(4.5)$$

with the introduction of parameter r, the degree of interconnection in eqn. (4.4) becomes variable. For r=0, the system is completely decoupled and for r=1, it is fully connected.

Initially we design stabilizers for all the machines neglecting the interconnection, (i.e. with r=0), with rotor velocity feedback, to assign the closed loop eigenvalues using the technique of Munro and Hirbod [31], utilized in chapter 2 and 3. Then the interconnection is introduced in small steps to update the parameters of PSS in such a way that the closed loop eigenvalues remain unchanged. Let the state equation and control law for PSS for the ith machine be, respectively.

$$\dot{\underline{Z}}_i = [S_i]\,\underline{Z}_i + R_i\,Y_{mi} \quad \ldots(4.6)$$

$$u_{mi} = [Q_i]\,\underline{Z}_i + K_i\,Y_{mi} \quad \ldots(4.7)$$

where Z_i represents the state variables of PSS. Eqns. (4.4) to (4.7) yield the dynamical equation and control law for the

augmented system (including PSS dynamics) of the ith unit as given below:

$$\underline{\dot{x}}_i = [A_{ii}]\underline{x}_i + r \sum_{\substack{j=1 \\ \neq i}}^{n} [A_{ij}]\underline{x}_j + [B_i]\underline{u}_i \qquad .....(4.8)$$

$$y_i = [C_{ii}]\ \underline{x}_i \qquad .....(4.9)$$

and

$$\underline{u}_i = [K_{di}]\ Y_i \qquad .....(4.10)$$

where $\underline{x}_i = [\underline{x}_{mi}^t\ \ \underline{z}_i^t\ ]^t$; $Y_i = [Y_{mi}\ \ \underline{Z}_i^t]^t$ ..

$$A_{ii} = \begin{bmatrix} A_{mii} & 0 \\ 0 & 0 \end{bmatrix} \quad ; \quad A_{ij} = \begin{bmatrix} A_{mij} & 0 \\ 0 & 0 \end{bmatrix}$$

$$B_i = \begin{bmatrix} b_{mi} & 0 \\ 0 & I \end{bmatrix} \quad ; \quad K_{di} = \begin{bmatrix} K_i & Q_i \\ R_i & S_i \end{bmatrix}$$

$$C_{ii} = \begin{bmatrix} C_{mii} & 0 \\ 0 & I \end{bmatrix}$$

For the composite power system, Eqns. (4.8) to (4.10) take the form

$$\underline{\dot{X}} = [A_D + rA_o]\ \underline{X} + [B_D]\ \underline{U} \qquad .....(4.11)$$

$$\underline{Y} = [C_D]\ \underline{X} \qquad .....(4.12)$$

$$\underline{U} = [K_D(r)]\ \underline{Y} \qquad .....(4.23)$$

where A_D = Block diagonal $[A_{11}, A_{12}, \ \ ...., \ A_{nn}]$

B_D = Block diagonal $[B_1, B_2 \ldots\ldots, B_n]$

C_D = Block diagonal $[C_{11}, C_{22} \ldots\ldots, C_{nn}]$

K_D = Block diagonal $[K_{d1}, K_{d2} \ldots\ldots, K_{dn}]$

$$A_o = \begin{bmatrix} 0 & A_{12} & A_{13} & \cdots & A_{1n} \\ A_{21} & 0 & A_{23} & \cdots & A_{2n} \\ \vdots & & & & \\ A_{n1} & A_{n2} & A_{n3} & \cdots & 0 \end{bmatrix}$$

The objective is to find a control law $\underline{U}$, such that the composite power system (eqn. (4.11)),has desired eigenvalues The eigenvalues of the composite system are the eigenvalues of the closed-loop matrix

$$F(r) = A_D + rA_o + B_D K_D(r) C_D$$

At r=0, the matrix $K_D(0)$ can be easily computed, since the system is decoupled. Interconnection is then slowly introduc in small steps of Δr, and $K_D(r)$ is modified such that that the eigenvalues are not much disturbed in the presence of interconnections. This is easier than directly computing $K_D(1)$, the final answer.

The ith eigenvalue equation of the closed loop system can be written, for any value of r as

$$[\lambda_i(r) I - F(r)] \underline{V}_i(r) = \underline{0} \qquad \ldots.(4.14)$$

where $\underline{V}_i(r)$ is the right eigenvector associated with the eigenvalue $\lambda_i(r)$. The left eigenvector of the system is defined by

$$\underline{W}_j^*(r)\,[\lambda_j(r)I-F(r)] = \underline{0} \qquad \ldots.\ (4.15)$$

where $\underline{W}_j^*(r).\ \underline{V}_i(r) = 1 \quad \text{for } j = i$

$= 0 \quad \text{for } j \neq i$

In the above, * indicates conjugate transpose of the eigenvector $\underline{W}_j(r)$. Differentiating eqn. (4.14) with respect to r and premultiplying by $\underline{W}_i^*(r)$ we get

$$\underline{W}_i^*(r)\frac{d}{dr}\,[\lambda_i(r)I-F(r)]\,\underline{V}_i(r)+\underline{W}_i^*(r)\,[\lambda_i(r)I-F(r)]\,\frac{d}{di}\,\underline{V}_i(r) = 0 \qquad \ldots..(4.16)$$

It is obvious from eqn. (4.15) that the second term of eqn.(4.16 will be zero. Using the expression for F(r) and rearranging eqn (4.16), we get

$$\underline{W}_i^*[B_D\ \frac{dK_D}{dr}\ C_D]\,\underline{V}_i = \frac{d\lambda_i}{dr} - \underline{W}_i^*\,[A_o]\underline{V}_i \qquad \ldots.(4.17)$$

In eqn (4.17) $\frac{d\lambda_i}{dr}$ may be set equal to zero, so as to make eigenvalues insensitive to change in r. $\frac{dK_D}{dr}$ can be solved from eqn. (4.17) and utilized in updating K_D as follows

$$K_D\,(r+\Delta r) = K_D(r) + \frac{dK_D(r)}{dr}\Big|_r\,\Delta r \qquad \ldots.(4.18)$$

Solution of eqn. (4.17) is obtained by using the tensor product operation. Suppose $M = [m_{ij}]$ is of dimension pxq and L is of dimension rxs, then the tensor product of M by L ($M \otimes L$), is defined to be the prxqs matrix $[m_{ij}L]$. The 'vec' operation on the matrix $M = [M_1, M_2, \ldots, M_q]$, where M_i is the ith column of M, is defined as

$$\mathrm{Vec}(M) = \begin{bmatrix} M_1 \\ M_2 \\ \cdot \\ \cdot \\ \cdot \\ M_q \end{bmatrix}$$

It may be shown that the set of equations (4.17) for i=1,2,..,N, where N is the total number of states, is equivalent to

$$[\phi\ (r)]\ \mathrm{Vec}\ [\frac{dK_D(r)}{dr}] = \beta(r) \tag{4.19}$$

where

$$\phi(r) = \begin{bmatrix} [C_D\underline{V}_1]^t & \otimes & \underline{W}_1^* & B_D \\ [C_D\underline{V}_2]^t & \otimes & \underline{W}_2^* & B_D \\ \cdot & & \cdot & \\ \cdot & & \cdot & \\ \cdot & & \cdot & \\ [C_D\underline{V}_N]^t & \otimes & \underline{W}_N^* & B_D \end{bmatrix}$$

and

$$\beta(r) = \begin{bmatrix} \frac{d\ \ _1}{dr} - \underline{W}_2^*\ [A_o]\underline{V}_1 \\ \frac{d\ \ _2}{dr} - \underline{W}_2^*\ [A_o]\underline{V}_2 \\ \cdot \qquad \cdot \\ \cdot \qquad \cdot \\ \cdot \qquad \cdot \\ \frac{d\ \ _n}{dr} - \underline{W}_N^*[A_o]\underline{V}_N \end{bmatrix}$$

As K_D is a block diagonal matrix, columns of $\phi(r)$ corresponding to zero entries of Vec $(\frac{dK_D}{dr})$ are deleted to obtain $\phi(r)$. Eqn. (4.19) can now be written as

$$\phi(r) \begin{bmatrix} \mathrm{Vec}\left(\frac{dK_{d1}}{dr}\right) \\ \mathrm{Vec}\left(\frac{dK_{d2}}{dr}\right) \\ \vdots \\ \mathrm{Vec}\left(\frac{dK_{dN}}{dr}\right) \end{bmatrix} = \beta(r) \qquad \ldots(4.20)$$

From eqn.(4.20), solution for Vec $(\frac{dK_{di}}{dr})$, i=1,...,n, can be obtained by computing the pseudo-inverse of matrix $\phi(r)$. Solution of eqn. (4.20) in each iteration provides an update of $\frac{dK_D}{dr}$ which is used in eqn. (4.18) to update the feedback gain matrix K_D. The conditions for existance of a real solution of eqn. (4.20) were obtained in Ref. [25] to be the following

i) Each subsystem (machine and PSS) is controllable and observable.

ii) The eigenvalues of each subsystem can be assigned by local dynamic output feedback.

iii) At most one subsystem has an augmented state space which is of odd order. This condition guarantees that the feedback gains, i.e. matrix K_{di}, are real.

iv) Matrices B_D and C_D have full column and row rank respectively.

4.4 DESIGN ALGORITHM

The following algorithm Ref.[1] was used for PSS design in multimachine system.

Step 1 : Obtain state space equations of each machine as in eqns. (4.4) and (4.5).

Step 2 : Augment state equations of the machines with stabiliser dynamics as in eqns.(4.8) and (4.9).

Step 3 : Design feedback gain matrix $K_{di}(0)$ for each of the machines using local velocity feedback, to assign closed-loop eigenvalues to desired locations, by setting the parameter r=0 in eqn.(4.8).

Step 4 : Construct eqns.(4.11) to (4.13) for the composite system from eqns. (4.8) to (4.10) of individual machines.

Step 5 : Compute left and right eigenvector of the matrix F(r) .

Step 6 : Calculate $\phi(r)$ and $\beta(r)$ and solve eqn. (4.20) for $\frac{dK_D}{dr}$.

Step 7 : Update $K_D(r)$ as shown in eqn. (4.18), by selecting a sufficiently small value of Δr.

Step 8 : Increase the value of r to $r+\Delta r$.

Step 9 : Go to step 5 if r is less than or equal to unity. Print $K_D(r)$ when r > 1 and stop.

4.5 SYSTEM MODEL

A multimachine power system problem given in Ref.[46], consisting of 3 generators and 9 buses, is considered. A single line diagram of the system is shown in Fig.A 4.1. The system data used for PSS design are given in Appendix A-4. Each machine with its excitation system is represented by a fourth order model. Machine 1 is considered as reference for the measurements of rotor angle; it, therefore, has a third order model. The open loop system model is, thus, of eleventh order.

4.6 NUMERICAL RESULTS

We use only velocity feedback to design a second order PSS for each machine, with transfer function of the form

$$F(s) = \frac{\theta_o s^2+\theta_1 s+\theta_2}{s^2+\gamma_1 s+\gamma_2} \qquad \ldots(4.21)$$

The open loop system matrices are shown in the next page . Table 4.1 shows the open loop eigenvalues of the system.

Following the design technique as refered in section 6.4 of Ref [1] for pole assignment neglecting interconnections we develop three PSS for the three machines. Here we give a description of PSS designed in tabular form.

$$Am11=\begin{bmatrix}-0.1293 & 0.0 & -1.8356\\ -1.0310 & 0.0 & 0.0\\ 271.303 & 0.0 & -100.0\end{bmatrix}$$

$$Am12=\begin{bmatrix}0.0238 & 0.0 & -0.0063 & 0.0\\ 0.9213 & 0.0 & 12.1999 & 0.0\\ 44.236 & 0.0 & -40.041 & 0.0\end{bmatrix}$$

$$Am13=\begin{bmatrix}0.0344 & 0.0 & 0.0473 & 0.0\\ 0.8548 & 0.0 & 7.2381 & 0.0\\ 65.007 & 0.0 & 75.534 & 0.0\end{bmatrix}$$

$$bm1=\begin{bmatrix}0.0 & 0.0 & 2500.0\end{bmatrix}$$

$$Cm11=\begin{bmatrix}0.0 & 1.0 & 0.0\end{bmatrix}$$

$$Am21=\begin{bmatrix}0.01730 & 0.0 & 0.0\\ -1.7983 & 0.0 & 0.0\\ 0.0 & -1.0 & 0.0\\ 94.2625 & 0.0 & 0.0\end{bmatrix}$$

$$Am22=\begin{bmatrix}-0.51140 & 0.0 & -2.65610 & -1.39120\\ -10.7674 & 0.0 & -71.0929 & 0.0\\ 0.0 & 1.0 & 0.0 & 0.0\\ 215.8138 & 0.0 & 189.7026 & -66.6667\end{bmatrix}$$

$$Am23=\begin{bmatrix}0.206700 & 0.0 & 0.00000 & 0.0\\ 2.6601 & 0.0 & 22.6567 & 0.0\\ 0.0 & 0.0 & 0.0 & 0.0\\ 106.5345 & 0.0 & 90.1385 & 0.0\end{bmatrix}$$

$$bm2=\begin{bmatrix}0.0 & 0.0 & 0.0 & 2500.0\end{bmatrix}$$

$$Cm22=\begin{bmatrix}0.0 & 1.0 & 0.0 & 0.0\end{bmatrix}$$

$$Am31=\begin{bmatrix}0.03300 & 0.0 & 0.0\\ -1.2497 & 0.0 & 0.0\\ 0.0 & -1.0 & 0.0\\ 75.6676 & 0.0 & 0.0\end{bmatrix}$$

$$Am32=\begin{bmatrix}0.14830 & 0.0 & 0.997000 & 0.0\\ 5.44670 & 0.0 & 55.71570 & 0.0\\ 0.0 & 0.0 & 0.0 & 0.0\\ 54.6472 & 0.0 & -125.275 & 0.0\end{bmatrix}$$

$$Am33=\begin{bmatrix}-0.61980 & 0.0 & -2.160200 & -0.9365\\ -26.2893 & 0.0 & -124.5844 & 0.0\\ 0.0 & 1.0 & 0.0 & 0.0\\ 225.4484 & 0.0 & 371.1237 & -50.0\end{bmatrix}$$

$$bm3=\begin{bmatrix}0.0 & 0.0 & 0.0 & 2500.0\end{bmatrix}$$

$$Cm3=\begin{bmatrix}0.0 & 1.0 & 0.0 & 0.0\end{bmatrix}$$

O.	EIGENVALUES
	-0.427446+J8.252612
	-0.427446-J8.252612
	-0.880441+J11.913736
	-0.880441-J11.913736
	-2.068020+J0.0
	-3.659238+J0.0
	-7.976150+J0.0
	-44.96911+J0.0
	-61.84220+J0.0
	-94.79659+J0.0
	0.0+J0.0

TABLE 4.1 EIGENVALUES OF THE OPEN LOOP SYSTEM.

NO.	EIGENVALUES
	-0.268561+J0.0
	-1.196420+J8.195561
	-1.196420-J8.195561
	-1.272168+J0.041988
	-1.272168-J0.041988
	-1.593803+J12.150309
	-1.593803-J12.150309
	-2.067331+J0.0
	-2.444427+J0.0
	-3.035573+J0.0
	-3.754584+J0.0
	-9.685784+J0.0
	-16.377494+J0.0
	-43.946010+J0.0
	-48.069183+J0.0
	-61.941589+J0.0
	-94.798347+J0.0

TABLE 4.5 EIGENVALUES OF THE CLOSED LOOP SYSTEM.

	Machine 1	Machine 2	Machine 3
Open loop eigenvalues at r=0	0.0	-0.433541 $\pm j8.230556$	-0.983698 $\pm j11.021860$
	-5.393352	-4.532270	-3.272960
	-94.735936	-61.778666	-45.379431
Desired locations	-2.0, -3.0 -4.0	-2.20 $\pm j8.0$ -3.0	-3.0 $\pm$ j11.0 -3.0
Remaining Closed loop eigenvalues	-1.499999	-5.840128	-3.450304
	-94.736379	-13.210880	-39.758581
		-48.518170	-61.888380

Table 4.2 Eigenvalues of the 3-machine system at r=0

Table 4.3 shows the parameters of the three stabilizers obtained in the first stage of design. It is clear that since for every machine we specify only three locations, the pole placement is partial.

Machine	θ_o	θ_1	θ_2	γ_1	γ_2
1.	0.03485	0.121359	0.0900124	2.885756	1.456124
2.	0.299454	1.238136	0.897746	19.949938	42.967523
3.	0.612943	3.417337	6.138215	51.365486	151.31207

Table 4.3 PSS parameters for r = 0.

The feedback gain matrix K_{di} for ith machine can be obtained in terms of PSS parameters, defined in eqn. (4.21) as

$$[K_{di}] = \begin{bmatrix} \theta_{0i} & \theta'_{2i} & \theta'_{1i} \\ 0 & 0 & 1 \\ 1 & -\gamma_{2i} & -\gamma_{1i} \end{bmatrix} \qquad .... (4.23)$$

where

$$\theta'_{1i} = \theta_{1i} \quad -\theta_{0i} \quad \gamma_{1i}$$

and

$$\theta'_{2i} = \theta_{2i} \quad -\theta_{0i} \quad \gamma_{2i}$$

In the second stage of design, for updating the decentralized feedback gain matrix K_D, a step of $\Delta r = 0.05$ is chosen to introduce interconnection. The number of unknown in eqn. (4.20) are fifteen The order of closed-loop system is seventeen and therefore, eqn. (4.20) represents a set of seventeen simultaneous linear algebraic equations in fifteen unknowns. Pseudo inverse of $\emptyset(r)$, is determined for obtaining a solution of $\frac{dK_D}{dr}$ in eqn. (4.20). Table 4.4. shows the final values of Pss parameters with full interconnection, i.e. with r=1. Table 4.5 gives the closed loop eigenvalues obtained with PSS designed with interconnection, i.e., with PSS parameters given in Table 4.4.

Machine	θ_o	θ_1	θ_2	γ_1	γ_2
1.	0.0353845	0.1178504	0.0903524	2.385744	1.328615
2.	0.3969945	1.3364065	0.9102773	19.739929	43.239750
3.	0.6383817	3.5379695	6.2815793	50.264404	145.92301

Table 4.4 PSS Parameters for r = 1.

Table 4.5 gives the closed loop eigenvalues obtained with PSS of Table 4.4.

4.7 DISCUSSIONS

From Table 4.1 and 4.5 the advantage of providing PSS is clear. All the open-loop eigenvalues are pushed further into the left half of the S-plane; the oscillatory modes, related to rotor oscillation are further damped. The algorithm used was computationally efficient and was fairly accurate in arithmatic. One point is to be noted here is that since in designing all the three PSS, we chose second order PSS (unlike in Chapter 2 and 3), for second and third machine we had to do partial pole placement instead of complete pole placement . It is also observed that the remaining solitary unspecified pole of the closed loop system got placed well inside the left half plane, so, the performance of the closed loop system will not be adversely affected by this. However, this entire design was for non-adaptive PSS.

In the next section we shall describe the scheme for adaptive PSS, as already outlined in Fig. 4.1.

4.8 ADAPTIVE PSS FOR MULTIMACHINE SYSTEM

4.8.1 INTRODUCTION

As already proposed for the single machine case, we design three different PSS for each machine, for three distinctly different operating points. In the single machine case we had a 2- Dimensional operating space. Even in this simple multimachine case, the dimension of the space of operating conditions becomes six. So covering the whole range of feaseble operating conditions will be a rather difficult task and we will need considerably more number of PSS designed for each machine to cover the space of operating conditions satisfactorily. However, we have not investigated into this matter deeply, and our aim in this section is to prove that the idea used for design of composite PSS for single machine model will also give improved performance, if applied for the multimachine model. Two different weighting schemes, one based on change in system load and another based on machine load as already recommended in chapter 3 are presented in the next subsection.

4.8.2 WEIGHTAGES

Two different schemes for determining the weightages to be given to the different PSS when the operating

condition changes are considered. The first scheme is based on system loading. As may be observed from table 4.8, among the three design points, D-1 is comparatively lightly loaded and D -3 is heavily loaded. We have covered a range of total real and reactive loading on the system. For any system loading, the total complex load power delivered by the system is determined. The linear distances of this complex power from those at the three design points in the complex power plane decides the three weights to be associated with the three PSS. The weights are inversly propertional to their respective distances. Furthermore the sum of the three weightages should equal to unity. The numerical results using this proposition are presented in Table 4.6.

		W_1	W_2	W_3
Test Point 1 System Loads	Machine 1	0.4	0.4	0.2
$P_A = 120.0, Q_A = 45.0$				
$P_B = 85.0, Q_B = 25.0$	Machine 2	0.4	0.4	0.2
$P_C = 95.0 \quad Q_C = 30.0$	Machine 3	0.4	0.4	0.2
Test Point 2 System Loads				
$P_A = 130.0, Q_A = 55.0$	Machine 1	0.2	0.4	0.4
$P_B = 95.0, Q_B = 35.0$	Machine 2	0.2	0.4	0.4
$P_C = 105.0, Q_C = 40.0$	Machine 3	0.2	0.4	0.4

Table 4.6 Weights given to the PSS according to scheme 1.

The second scheme for determining weights is the same as the scheme used in the single machine case. The real and reactive powers generated by each machine are found out from load flow studies, and for each individual machine, the same technique as used in section 3.2, is applied, Table 4.7 gives the numerical results using this technique at the same test points.

		W_1	W_2	W_3
Test Point 1				
Generator outputs				
$P_{G1}=56.3728, Q_{G1}=-2.185$	Machine 1	0.4637	0.4193	0.1171
$P_{G2}=163.0, Q_{G2}=6.70$	Machine 2	0.3333	0.3333	0.3333
$P_{G3}=85.0, Q_{G3}=-10.9$	Machine 3	0.3333	0.3333	0.3333
Test Point 2				
Generator outputs				
$P_{G1}=87.2296, Q_{G1}=61.5441$	Machine 1	0.2794	0.4006	0.3200
$P_{G2}=163.0, Q_{G2}=6.70$	Machine 2	0.3333	0.3333	0.3333
$P_{G3}=85.0, Q_{G3}=-10.9$	Machine 3	0.3333	0.3333	0.3333

Table 4.7 Weights given to the PSS according to scheme 2.

4.8.3 ALGORITHM FOR ADAPTIVE PSS

The algorithm used for adaptive PSS can be described as follows:

Step 1 : Select three different operating points at which PSS are to be designed .

Step 2 : Design PSS for each operating points, following the same procedure as in the non adaptive case.

Step 3 : Determine weightages to be given to the PSS designed for any given operating condition using one of the two methods given in previous subsection.

4.8.4 NUMERICAL RESULTS

Following the algorithm described above, numerical results have been obtained for two typical operating conditions which occur within the range of operating conditions covered by the design points considered. Table 4.8 gives the details of PSS designed at the three preselected design points. Table 4.9 gives the details of the composite adaptive PSS for the two test points. It also gives a comparison between use of non-adaptive and adaptive PSS. First column in the Table gives the closed loop eigenvalues obtained with the non-adaptive PSS designed for design point D-1. Second and third columns of the table give the closed loop eigenvalues with the composite adaptive PSS, using scheme 1 and scheme 2 respectively, for determining the weights.

4.9 DISCUSSION

As may be observed from Table 4.9, the improvement achieved by using the adaptive schemes is not much. It is

LOAD AND GENERATOR CONDITIONS (FROM LOAD FLOW)	D0	D1	D2	Y1	Y2	EIGENVALUES OF OPEN LOOP SYSTEM WITHOUT PSS	ASSIGNED CLOSED LOOP EIGENVALUES WITH K0(r) AT r=1
DESIGN POINT D-1	PSS FOR M/C-1					0.0+j0.0	-0.268551+j0.0
SYSTEM LOADS	0.03539	0.11785	0.09035	2.38574	1.32862	-0.427446+j8.252612	-1.195420+j8.190551
PA=115.0						-0.427446-j8.252612	-1.195420-j8.190551
QA=[illegible].0	PSS FOR M/C-2					-0.880441+j11.913736	-1.272153+j[illegible]
PB=9[illegible].0	0.39539	1.33641	0.91028	19.7399	43.2397	-0.880441-j11.913736	-1.272153-j[illegible]
QB=2[illegible].0						-2.068020+j0.0	-1.593813+j12.[illegible]
PC=9[illegible].0	PSS FOR M/C-3					-3.659238+j0.0	-1.593813-j12.[illegible]
QC=25.0	0.53838	3.53797	5.28158	50.2644	145.923	-7.975150+j0.0	-2.067341+j0.0
GENERATOR OUTPUTS						-44.95911+j0.0	-2.444427+j0.0
						-51.84221+j0.0	-3.035573+j0.0
						-94.79659+j0.0	-3.754544+j0.0
PG1=41.3143							-9.685744+j0.0
QG1=-27.9091							-16.37749+j0.0
PG2=163.0							-43.94611+j0.0
QG2=6.70							-48.05913+j0.0
PG3=85.0							-61.94153+j0.0
QG3=-10.9							-94.79855+j0.0
DESIGN POINT D-2						0.0+j0.0	-0.325447+j0.0
	PSS FOR M/C-1					-0.33733+j8.07009	-1.234311+j0.0
SYSTEM LOADS	0.03479	0.10956	0.02553	2.38574	1.32862	-0.33733-j8.07009	-1.242913+j7.909296
PA=125.0						-0.82079+j11.6194	-1.242913-j7.909295
QA=5[illegible].0						-0.82079-j11.6194	-1.442376+j0.0
PB=9[illegible].0	PSS FOR M/C-2					-2.09866+j0.0	-1.998225+j0.0
QB=3[illegible].0						-3.569304+j0.0	-2.155918+j12.912448
PC=1[illegible]0.0	0.57294	1.62858	1.71379	19.7399	43.2398	-7.917287+j0.0	-2.155918-j12.912448
QC=35.0						-45.227659+j0.0	-2.408775+j0.0
GENERATOR	PSS FOR M/C-3					-52.051077+j0.0	-3.097418+j0.0
OUTPUTS						-94.858380+j0.0	-3.781040+j0.0
PG1=71.6407	0.52752	3.28869	4.32770	50.2644	145.923		-10.494538+j0.0
QG1=27.9305							-15.634732+j0.0
PG2=163.0							-41.385162+j0.0
QG2=6.70							-48.357232+j0.0
PG3=85.0							-62.416495+j0.0
QG3=-10.9							-94.061237+j0.0
DESIGN POINT D-3						0.0+j0.0	-1.162141+j0.0
	PSS FOR M/C-1					-0.087598+j7.69008	-2.0740+j10.79794
SYSTEM LOADS	0.02557	0.04779	0.20623	2.38574	1.32862	-0.087598-j7.69008	-2.0740-j10.79794
PA=135.0						-0.567250+j11.0140	-1.253573+j8.01411
QA=5[illegible].0	PSS FOR M/C-2					-0.567250-j11.0140	-1.253573-j8.01411
PB=1[illegible]0.0	0.15502	2.44751	3.83066	19.7399	43.2397	-2.010098+j0.0	-1.356421+j0.203723
QB=4[illegible].0						-3.756856+j0.0	-1.356421-j0.203723
PC=[illegible]5.0	PSS FOR M/C-3					-7.590745+j0.0	-2.022045+j0.0
QC=45.0	0.58559	5.28171	7.19094	50.2644	145.923	-45.564651+j0.0	-2.626119+j0.0
GENERATOR						-52.401209+j0.0	-3.253275+j0.0
OUTPUTS						-94.917018+j0.0	-3.983076+j0.0
PG1=103.4359							-8.44085+j4.031213
QG1=106.0916							-8.44085-j4.031213
PG2=163.0							-45.065804+j2.938835
QG2=6.70							-45.065804-j2.938835
PG3=85.0							-62.515454+j0.0
QG3=-10.9							-94.045137+j0.0

TABLE 4.8 NON ADAPTIVE PSS AT THREE DESIGN POINTS.

	ACCORDING TO WEIGHING SCHEME-1	ACCORDING TO WEIGHING SCHEME-2	CLOSED LOOP EIGENVALUES WHEN PSS DESIGNED FOR D=1 ARE ARE USED	CLOSED LOOP EIGENVALUES WITH PSS OF SCHEME-1	CLOSED LOOP EIGENVALUES WITH PSS OF SCHEME-2
D0	0.0333855	0.034105	-0.316312+j0.0	-0.357861+j0.0	-0.365611+j0.0
D1	0.1085042	0.1108452	-0.779447+j0.0	-0.745829+j0.0	-0.746559+j0.0
D2	0.0876389	0.0895314	-1.50+j0.0	-1.50+j0.0	-1.50+j0.0
D0	0.3875603	0.385283	-1.510239	-1.838256	-1.931071
D1	1.6755165	1.804199	+j8.045574	+j8.00435	+j8.01051
D2	1.9157242	2.1515473	-2.022134+j0.0	-2.020521+j0.0	-2.020865+j0.0
D0	0.5234621	0.617357	-2.505534+j0.0	-2.50485+j0.0	-2.504959+j0.0
D1	3.7870071	4.0361284	-2.899813	-2.910313	-2.909652
D2	5.551002	5.9334088	+j12.425521	+j12.338436	+j12.351848
			-3.258421+j0.0	-3.111705+j0.0	-3.134730+j0.0
			-3.832722+j0.0	-3.960239+j0.0	-3.909194+j0.0
			-10.085959	-11.237399	-11.245554
			+j3.30271	+j2.42914	+j2.632494
			-37.23201+j0.0	-39.282083+j0.0	-38.970984+j0.
			-47.23519+j0.0	-49.171798+j0.0	-47.986551+j0.
			-61.97339+j0.0	-61.968474+j0.0	-61.959573+j0.
			-94.82813+j0.0	-94.82850+j0.0	-94.928465+j0.
D0	0.0313769	0.0321767	-0.515527	-0.503491	-0.504927
D1	0.1019699	0.1045717	+j0.234022	+j0.108777	+j0.131226
D2	0.0823568	0.0844599	-1.49999+j0.0	-1.50+j0.0	-1.50+j0.0
D0	0.3829407	0.385283	-1.956838	-2.08320	-2.050737
D1	1.8977575	1.804199	+j7.662545	+j7.744399	+j7.728235
D2	2.3998013	2.1515473	-2.499503+j0.0	-2.499801+j0.0	-2.499747+j0.
D0	0.5128855	0.6171357	-2.895794	-2.859503	-2.873949
D1	4.1357557	4.0361248	+j10.679304	+j10.627686	+j10.574064
D2	5.9537717	5.9334088	-2.953353+j0.0	-2.992710+j0.0	-2.988049+j0.
			-3.273533+j0.0	-3.350689+j0.0	-3.335421+j0.
			-5.143154+j0.0	-5.168255+j0.0	-5.165111+j0.
			-6.297379+j0.0	-6.994061+j0.0	-6.751749+j0.
			-12.92433+j0.0	-10.433693+j0.0	-10.902749+j0
			-40.00359+j0.0	-39.160761+j0.0	-39.308475+j0
			-48.61103+j0.0	-48.157585+j0.0	-48.227717+j0
			-62.23251+j0.0	-62.225616+j0.0	-62.226751+j0
			-94.94352+j0.0	-94.913432+j0.0	-94.943412+j0

TABLE 4.9 ADAPTIVE PSS AT TWO TEST POINTS.

nevertheless, true that there is some improvement and the oscilatory modes related to rotor oscillation are particularly better damped by the adaptive controller designed. It is also true that the number of design points used is small. This was because of the complexity involved and the time taken for computation. The schemes proposed for determining weightages are simple and convenient to use. However, they are adhoc and lack theoretical basis. One feels that if more number of design points are considered so as to cover a wider range of operating condition and a better scheme for determining the weightages is used, the performance of the closed loop system will show considerable improvement.

CHAPTER 5

CONCLUSION

Traditional nonadaptive PSS designs are satisfactory over a small range of operating conditionsaround that for which the PSS is designed. There is, therefore, need for developing adaptive PSS designs, which hold over a wide range of operating conditions. Coventional adaptive designs are complex and involve on-line identification of model parameters which undergo variation. Practical implementation of such PSS is not simple. The need for developing simpler adapation schemes is therefore, clear. This thesis has addressed itself to this task.

The idea used in the design is to have a number of PSS, working simultaneously and in parallel. The control input to the excitation system is obtained as a weighted sum of the outputs of the various PSS. Each PSS is designed for a particular operating condition. A wide range of operating conditions can be covered by designing a sufficient number of PSS. For any given operating condition, the weights for obtaining the weighted sum of the outputs of the various PSS are given by a simple rule.

The above concept of adaptation has been examined in detail for a single-machine-infinite-bus system. It has been found that a relatively small number of PSS will yield good

system performance over a wide range of operating conditions. This scheme, is therefore, simple and superior to the traditional nonadaptive schemes. It is also better than the traditional adaptive schemes from the implementation point of view. The additional hardware requirement is not much, in this scheme.

Design of the proposed adaptive PSS scheme has also been examined in a simple multimachine system, involving three generators and nine buses. Here, complexity involved in PSS design increases significantly. It is also seen that this adaptation procedure to choose the relative weights in the PSS cannot be chosen, by a simple procedure as in the single machine case, with a fair degree of certainty regarding the outcome. However, two schemes have been examined, and improvement in system performance established. More work needs to be done in developing better algorithms for determining the weights to be attached to the individual PSS and also for determining the number and values of operating conditions for which the individual PSS are to be designed. In any case, the investigations so far done and reported here appear to be promising.

REFERENCES

1. A. Anwar, ' Investigations into design of power system stabiliser' Ph.D. Thesis, I.I.T. Kanpur, 1985.

2. F.P. De Mello and C. Concordia, 'Concepts of synchronous machine stability as affected by excitation control', IEEE Trans. PAS-88, pp. 316-329, April 1969.

3. K. Bollinger and A. Laha, ' Power system stabiliser design using root locus methods', IEEE Trans . PAS-94, pp.1484-1488, Sept./Oct. 1975.

4. F.M. Hughes and A.M.A. Hamdan, ' Design of turboalternator excitation controllers using multivariable frequency response methods', Proce. IEEE, pp. 901-905, Sept. 1976.

5. A.M.A. Humdan and F.M. Hughes, ' Analysis and design of power system stabilizers', Int. J. of control, pp.769-786, Nov. 1977.

6. Y.N.Yu, K. Vongsuriya and L.N. Wedman,' Application of an optimal control theory to a power system', IEEE Trans. PAS-89, pp. 55-62, Jan. 1970.

7. J.H. Anderson, ' The control of a synchronous machine using optimal control theory', Proce. IEE, pp.25-35, Jan. 1971.

8. S. Raman and S.C. Kapoor, ' Synthesis of optimal regulator for synchronous machine', Proce. IEE, Vol. 119, pp.1383-1390, Sept. 1972.

9. Y.N.Yu and C. Siggers, ' Stabilization and optimal control signals for a power system', IEEE Trans. PAS-90, pp. 1469-1481, 1971.

10. E.J. Davison and N.S. Rao, ' Optimal output feedback control of a synchronous machine', IEEE Trans. PAS-90, pp. 2123-2134, Sept. /Oct. 1971.

11. W.S. Levine and M. Athans, ' On the determination of the optimal constant output feedback gains', IEEE Trans. Automatic control, Vol. AC-15, pp.44-48, Feb. 1970.

12. De Sarkar and N. Dharma Rao, ' Stabilization of a synchronous machine through output feedback control', IEEE Trans. PAS-92, pp. 159-160, Jan./ Feb. 1973.

13. W.N. Wonham, ' On pole placement in multi-input controllable linear system', IEEE Trans. Automatic control, Vol. Ac-12, pp. 660-665, 1967.

14. B. Porter and R. Crossley, Modal control theory and applications. Taylor and Francis Ltd. 1972.

15. D.Q. Mayne and P. Murdoch, 'Modal control of linear time invariant systems', Int. J. of control, Vol.11, pp. 223-227,1970.

16. B.S. Morgan,' Sensitivity analysis and synthesis of multivariable systems', IEEE Trans. Automatic control, pp. 506-512, July 1966.

17. H. Seraji, ' A new method for pole placement using output feedback', Int. J. of control, Vol.28, pp.147-155, 1978.

18. E.J. Davison and S.H. Wang, ' On pole assignment in linear multivariable systems using output feedback', IEEE Trans. Automatic control, pp.516-518, Aug. 1975.

19. H. Kimura, ' Pole assignment by gain output feedback', IEEE Trans. Automatic control, pp. 509-516, Aug. 1975.

20. H. Kimura, ' On pole assignment by output feedback', Int. J. of control, Vol.28, No.1, pp.11-22, 1978.

21. E.J. Davison and S.H. Wang, ' Properties of linear time invariant multivariable system subject to arbitrary output and state feedback', IEEE Trans. Automatic control, Vol. AC-18, pp. 24-32, Feb. 1973.

22. K.R. Padiyar, S.S. Prabhu, M.A. Pai and K. Gomathi, ' Design of stabilizers by pole assignment with output feedback', Electrical power and energy system, Vol. 2, pp.140-146, July 1980.

23. V. Arcidiacono, E. Ferrari, R. Marcorato, J. Dos Ghali and D. Grandy, ' Evaluation and improvement of electro-mechanical oscillation damping by means of eigenvalue eigenvector analysis, practical results in the central power system', IEEE Trans. PAS-99, pp. 769-778, March/ April 1980.

24. R.J. Fleming, M.A. Mohan and K. Parvatism, ' Selection of parameters of stabilizers in multimachine power systems', IEEE Trans. PAS-100, pp. 2329-2333, May 1981.

25. S. Lefebvre, S. Richter and R. Decarlo, ' Decentralised control of linear interconnected multivariable system', Proce. of IEEE conference on Decision and control, pp. 525-529, 1980.

26. S. Abe and A. Doi, ' A New power system stabilizer synthesis in multimachine power systems', IEEE Trans. PAS-102 pp. 3910-3918, Dec. 1983.

27. A. Doi and S. Abe, ' Co-ordinated synthesis of power system stabilizers in multimachine power system', IEEE Trans. PAS-103, pp. 1473-1479, June 1984.

28. A. Ghosh, ' Adaptive stabilizers for generator excitation', Ph.D. Thesis, University of Calgary, Alberta, Sept. 1983.

29. J. Kannaiah, O.P. Malik and G.S. Hope, ' Excitation control of synchronous generators using adaptive regulators; Part I: Theory and simulation results; Part II: Implementation and test results', IEEE Trans. PAS-103, pp. 897-910, May 1984.

30. A. Ghosh, G. Ledwich, O.P. Malik and G.S. Hope, ' Power system stabilizer based on Adaptive control techniques', IEEE Trans. PAS-103, pp. 1983-1989, Aug. 1984.

31. N. Munro and S.N. Hirbod, ' Pole assignment using full rank output feedback compensators', Int. J. of system science, Vol. 10, pp. 285-306, 1979.

32. O.H. Abdalla, S.A.Hassan, N.T. Tweig, ' Co-ordinated Stabilization of a multimachine power system', IEEE Trans. PAS-103, pp.483-494, March 1984.

33. S. Lefebvre, ' Tuning of stabilizers in multimachine power systems', IEEE Trans. PAS-102, pp. 290-299, Feb. 1983.

34. K. Gomathi,' Pole assignment techniques for power system stabilization', Ph.D. Thesis, I.I.T. Kanpur, India, 1979.

35. H.M. Ellis, J.E. Hardy, A.L. Blythe and J.W. Skooglund, ' Dynamic stability of the peace river transmission systems', IEEE Trans. Power Apparatus and systems, Vol. PAS-85, pp. 586-60C, June 1966.

36. O.W. Hanson, C.J. Goodwin and P.L. Dandeno, 'Influence of excitation and speed control parameters in stabilizing intersystem oscillations', IEEE Trans. power apparatus and systems, Vol. PAS-87, pp.1306-1313, May 1968.

37. R.T. Byerly, F.W. Keay and J.M. Skooglund, 'Damping of power oscillations in salient pole machines with static exciters', IEEE Trans. Power apparatus and systems, Vol. PAS-89, pp. 1009-1021, July/Aug. 1970.

38. W. Watson and G. Manchur, 'Experience with supplementary damping signals for generator static excitation systems', IEEE Trans. Power Apparatus and systems, Vol. PAS-92, pp. 199-203, Jan./Feb. 1973.

39. P.A. Rusche, D.L. Hackett, D.H. Baker, G.E. Gareis and P.C. Kraus, ' Investigation of the dynamic oscillations of the Ludington pumped storage plant', IEEE Trans. Power apparatus and systems, Vol. PAS-95, pp. 1854-1862. Nov./Dec. 1976.

40. H.B. Gooi, E.F. Hill, M.A. Mobarak, D.H. Throne and T.H. Lee, ' Coordinated multmachine stabiliser setting without eigenvalue drift', IEEE Trans. Power apparatus and systems, Vol. PAS-100, pp.3879-3887, 1981.

41. Y. Obata, S. Takeda and H. Suzuki, ' An efficient eigenvalue estimation technique for multimachine power system dynamic stability analysis', IEEE Trans. Vol. PAS - 100, pp. 259-263, 1981.

42. C.M. Lim, and S. Elangovan, ' A new stabiliser design technique for multimachine power systems', IEEE Trans. Vol. PAS-104, pp. 2393-2400, Sept. 1985.

43. H. Seraji, ' Pole assignment using dynamic compensators with prespecified poles', International Journal of control, Vol. 22, No.2, pp.271-279, 1975.

44. L. Shaw, ' Pole placement: Stability and sensitivity of dynamic compensator', IEEE Trans. Automatic control, AC. 16, pp.210, April 1971.

45. S.S. Singh, ' Pole placement techniques using static and dynamic output feedback ' M.Tech. thesis, I.I.T. Kanpur, Aug. 1981.

46. Anderson and Fouad, ' Power system stability and control', IOWA State University Press, AMES, IOWA, USA. 1977.

47. E.V. Larsen and D.A. Swann, ' Applying power system stabilizers; Part I: General concepts; Part II: performance objectives and tuning concepts; Part III: Practical considerations', IEEE Trans. Power Apparatus and Systems, Vol. PAS-100, pp.3017-3046, June 1981.

48. C.T. Chen and C.H. Hsu, ' Design of dynamic compensators for multivariable systems', Proce. Joint Automatic control Conference, pp. 893-900, 1971.

49. IEEE Committee Report, ' Computer Representation of Excitation systems', IEEE Trans. Power Apparatus and systems, Vol. PAS-87, pp. 1460-1464, June 1968.

50. F.P. De Mello, P.T. Nolan, T.F. Laskowski and J.M. Undrill, ' Coordinated application of stabilisers in multimachine power systems,' IEEE Trans. PAS-99, pp.892-901 May/June 1981.

51. C. Radhakrishna, ' Stability Studies of AC/DC Power Systems', Ph.D.Thesis, I.I.T. Kanpur, 1980.

52. M.A. Pai, K.R. Padiyar and C. Radhakrishna, ' Synthesis of damping action in power systems using eigenvalue sensitivities', JIE (India), Vol.65, Pt. EL4, pp.127-131, Feb. 1985.

APPENDIX A- 1

STATE SPACE MODEL FOR SINGLE MACHINE SYSTEM

Here we consider a three winding synchronous machine model. The stator of the machine is represented by a dependent current source. A single phase equivalent circuit of the power system network is shown in Fig. 2.1 (b).

The system equations can be written as [34]:

$$\frac{2H}{\omega_o} p^2\partial = T_m - T'_e \quad \text{...(A 1.1)}$$

where

$$T'_e = X'_d \, (I_d i_q - I_q i_d) \quad \text{...(A 1.2)}$$

$$\dot{I}_d = [E_{fd} - X'_d I_d - (X_d - x'_d)\, i_d]/(X'_d T'_{do}) \quad \text{...(A 1.3)}$$

$$I_q = \eta \, i_q \quad \text{...(A 1.4)}$$

$$\eta = (X'_d - X_q)/X'_d$$

From Fig. 2.1 (b) , the armature current plasor i can be solved by using the mesh equations

$$\hat{i} = \frac{jX'_d}{j(X+X'_d)} \hat{I} - \hat{y}E \quad \text{...(A 1.5)}$$

where

$$\hat{y} = \frac{1}{j(X+X'_d)} = y_1 + jy_2 \quad \text{...(A 1.6)}$$

Let

$$a_1 + ja_2 = \frac{jX'_d}{j(X+X'_d)} \quad \text{...(A 1.7)}$$

where

$$a_1 = \frac{X'_d(X+X'_d)}{(X+X'_d)^2} = \frac{X'_d}{(X+X'_d)} \quad \text{...(A 1.8)}$$

and $a_2 = 0$ .... (A 1.9)

From eqn. (A 1.5)

$$i_q - j i_d = (a_1 + j a_2)(I_q - j I_d) + (y_1 + j y_2) E(\cos\delta - j\sin\delta) \quad \text{.... (A 1.10)}$$

Equating real and imaginary parts we get

$$i_q = a_1 I_q + E(y_1 \cos\delta + y_2 \sin\delta) \quad \text{.... (A 1.11)}$$

and

$$i_d = a_1 I_d - E(y_2 \cos\delta - y_1 \sin\delta) \quad \text{.... (A 1.12)}$$

Using eqn. (A 1.4)

$$i_q = \frac{E}{1 - a_1 \eta} (y_1 \cos\delta + y_2 \sin\delta) \quad \text{.... (A 1.13)}$$

and

$$i_d = a_1 I_d - E(y_2 \cos\delta - y_1 \sin\delta) \quad \text{.... (A 1.14)}$$

From eqn. (A 1.16)

$$y_1 = 0 \text{ and } y_2 = -\frac{1}{(X + X'_d)}$$

In equn. (A 1 .13) and (A 1.14), i_d and i_q are expressed in terms of I_d and δ only.

EXCITATION SYSTEM MODEL

Many excitation system are used in practice. Ref. [49] gives a detailed survey of all the practical excitation systems. In this work, a static excitation system, whose block diagram is shown in Fig. 2.1 (c), is considered.

In derivation of excitation system dynamics the time constant T_e of static exciter may be neglected, since it is small. Thus the state equation can be written as

$$\dot{X}_1 = - X_1/T_R+(K_R/T_R)V_t \qquad \text{....(A 1.15)}$$

Where

$$V_t = [V_d^2 + V_q^2]^{1/2}$$

The park's components of the terminal voltage V_d and V_q can be written as [34]

$$V_d = X_q i_q \qquad \text{....(A 1.16)}$$

and

$$V_q = X_d' (I_d - i_d) \qquad \text{...(A 1.17)}$$

From Fig 2.1 (c)

$$E_{fd} = V_{ref} - X_1 + u \qquad \text{...(A 1.18)}$$

LINEARIZED MODEL

We obtain the linearized model from eqns. (A 1.1), (A 1.3) and (A 1.15). For doing so we eliminate the non-state variables Δi_d and Δi_q which are obtained by linearizing eqns. (A 1.13) and (A 1.14).

$$\Delta i_q = K_1 \Delta I_d + K_2 \Delta \delta \qquad \text{...(A 1.19)}$$

$$\Delta i_d = K_3 \Delta I_d + K_4 \Delta \delta \qquad \text{...(A 1.20)}$$

where $K_1 = 0$, $K_2 = \frac{E}{1-a_1\eta}(y_1 \sin\partial_o - y_2\cos\partial_o)$,

$$K_3 = a_1 \text{ and } K_4 = E\,[-y_2 \sin\partial_o - y_1\cos\partial_o] \qquad \ldots(A\ 1.21)$$

Thus, the resulting fourth order system equation can be written as

$$\dot{\underline{X}} = A\underline{X} + bV \qquad \ldots(A\ 1.22)$$

where $\underline{X} = [\Delta I_d, \Delta\partial, \Delta\omega, \Delta X_1]^t$

and $V = \Delta u$

$$A = \begin{bmatrix} a_{11} & a_{12} & 0 & a_{14} \\ 0 & 0 & 1 & 0 \\ a_{31} & a_{32} & 0 & 0 \\ a_{41} & a_{42} & 0 & a_{44} \end{bmatrix} \text{ and } b = \begin{bmatrix} b_1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad \ldots.(A\ 1.23)$$

where

$$a_{11} = -[X'_d + (X_d - X'_d)K_3]/(X'_d T'_{do})$$

$$a_{12} = -K_r(X_d - X'_d)/(X'_d T'_{do})$$

$$a_{14} = -1/(X'_d T'_{do})$$

$$a_{31} = -\frac{\omega_o}{2H}(i_{qo} - K_3 I_{qo})X'_d$$

$$a_{32} = \frac{\omega_o}{2H}(K_4 I_{qo} - K_2 I_{do} + K_2 i_{do}\eta)X'_d \qquad \ldots.(A\ 1.24)$$

$$a_{41} = \frac{K_R}{T_R}\left[\frac{V_{qo}}{V_{to}} XK_3\right]$$

$$a_{42} = \frac{K_R}{T_R}\left[\frac{V_{do}}{V_{to}}(E\cos\partial_o - XK_2) + V_{qo}/V_{to}(-E\sin\partial_o + XK_4)\right]$$

$$a_{44} = -1/T_R \qquad b_1 = 1/(X'_d T'_{do})$$

APPENDIX A - 2

DERIVATION OF SYSTEM MATRICES

The system data considered are as follows (All values are in P.U.)

Generator parameters $X_d = 1.14$, $X_q = 0.66$, $X'_d = 0.24$

$T'_{do} = 12.0$, $H = 1.5$, $\omega_o = 314.0$

$K_R = 50.0$, $T_R = 0.01$ sec.

Network Parameters $R = 0.0$, $X = 0.7$

Operating Data $E = 1.0 \angle 0^o$

P = Received real power = 0.8

Q = Received reactive power = 0.6

The elements of the system matrices can be calculated in the following way.

$$V_t \angle \theta_o = E \angle 0^o + Zi$$

$$= 0.58 + j0.56 = 0.8062 \angle 43.995$$

Therefore $\theta_o = 43.995^o$

Now , $P_g + jQ_g = V_t \angle \theta_o \cdot i^* = 0.8 + j0.1$

Therefore $p_g = 0.8$ and $Q_g = 0.1$

Furthermore ,

$$\phi_o = \tan^{-1}\left(\frac{Q_g}{P_g}\right) = 7.125^o$$

$$i_{ao} = P_g/V_t \cos\phi_o = 1.0 = i$$

$$\beta_{go} = \tan^{-1}\left[\frac{i_{ao}X_q\cos\phi_o - i_{ao}r_a\sin\phi_o}{V_t + i_{ao}r_a\cos\phi_o + i_{ao}X_q\sin\phi_o}\right]; \ [r_a=0]$$

$$= 36.407^o$$

$$\delta_o = \beta_{go} + \theta_o = 80.402^o$$

$$V_{do} = V_t \sin\beta_{go} = 0.4785$$

$$V_{qo} = V_t \cos\beta_{go} = 0.6488$$

$$i_{do} = i_{ao}\sin(\beta_{go}+\phi_o) = 0.6888$$

$$i_{qo} = i_{ao}\cos(\beta_{go}+\phi_o) = 0.7250$$

$$I_{do} = \frac{V_{qo}}{X'_d} + i_{do} = 3.3921$$

$$I_{qo} = \eta\, i_{qo} = -1.26875$$

Now using the formulae given in Appendix A-1 we get

$a_{11} = -0.16312$	$a_{12} = -0.3278$	$a_{14} = -0.34722$
$a_{31} = -26.34$	$a_{32} = -47.5885$	$a_{41} = 719.0961$
$a_{42} = -773.2739$	$a_{44} = -100.0$	$b_1 = 0.34722.$

APPENDIX A - 3

POLE ASSIGNMENT WITH OUTPUT FEEDBACK [31]

The technique given here is based on the work of Munro and Hirbod [31]. The method presented in [31] provides a technique for the design of full-rank compensators for multivarible linear systems. Here the technique is restricted to single input linear systems

$$\underline{\dot{X}} = [A]\,\underline{X} + \underline{b}\,u \qquad \text{... (A 3.1)}$$

and

$$\underline{Y} = [C]\,\underline{X} \qquad \text{... (A 3.2)}$$

where, $X \in R^n$, $u \in R^1$ and $\underline{Y} \in R^r$ are respectively vectors of state, input and output variables. The r X 1 open-loop transfer function matrix G(s) is

$$G(s) = C(sI-A)^{-1}\,b = \frac{1}{\mu_o(s)} \begin{bmatrix} N_1(s) \\ \vdots \\ N_r(s) \end{bmatrix} \qquad \text{... (A 3.3)}$$

where

$$\mu_o(s) = s^n + \alpha_1 s^{n-1} + \ldots + \alpha_n \qquad \text{....(A. 3.4)}$$

and

$$N_i(s) = \beta_{i1} s^{n-1} + \beta_{i2} s^{n-2} + \ldots + \beta_{in} \qquad \text{....(A 3.5)}$$

$\mu_o(s)$ is the characteristic polynomial of G(s). Consider the output feedback law

$$u\,(s) = u_r(s) - F(s).\,Y(s) \qquad \text{.....(A 3.6)}$$

where $u_r \in R^1$ represents the reference input .

The problem can be defined as the determination of 1 X r dynamic feedback compensator, F(s), such that the closed-loop system

$$H(s) = [I + G(s)\ F(s)]^{-1}\ G(s) \qquad \text{.... (A 3.7)}$$

has a desired set of eigenvalues. The kth order compensator F(s) has the form

$$F(s) = \frac{1}{\mu_c(s)}\ [M_1(s), M_2(s),\ \ldots,\ M_r(s)] \qquad \text{...(A 3.8)}$$

where

$$\mu_c(s) = s^k + \gamma_1 s^{k-1} + \gamma_2 s^{k-2} + \ldots + \gamma_k \qquad \text{...(A 3.9)}$$

and

$$M_i(s) = \theta_{io} s^k + \theta_{i1} s^{k-1} + \ldots + \theta_{ik} \qquad \text{... (A 3.10)}$$

$\mu_c(s)$ is the characteristic polynomial of compensator transfer function F(s) .

The resulting closed -loop system characteristic polynomial $\mu_d(s)$, defined as :

$$\mu_d(s) = s^{n+k} + d_1 s^{n+k-1} \ldots. + d_{n+k} \qquad \text{.... (A 3.11)}$$

can be written as [31]

$$\mu_d(s) = \mu_o(s).\ \mu_c(s) + \sum_{i=1}^{r} N_i(s).M_i(s) \qquad \text{(A 3.12)}$$

COMPLETE POLE ASSIGNMENT

The problem of pole assignment can be defined as: given $\mu_o(s)$, $N_1(s)$, ..., $N_r(s)$ and a desired set of closed-loop poles, find $\mu_c(s)$, $M_1(s)$, ..., $M_r(s)$ of lowest degree which satisfy eqn. (A 3.12). Equating coefficients of like powers of s in eqn. (A 3.12), we get

$$[X_k]\,\underline{P}_k = \underline{\partial}_k \qquad \ldots\ldots \text{(A 3.13)}$$

where

$$[X_k] = \begin{bmatrix} 1 & 0 & \cdots & 0 & \beta_{11} & \cdots & 0 & \beta_{r1} & \cdots & 0 \\ \alpha_1 & 1 & \cdots & 0 & \beta_{12} & \cdots & 0 & \beta_{r2} & \cdots & 0 \\ \alpha_1 & \alpha_1 & & & \cdot & \cdots & & & & \\ \cdot & \alpha_2 & & 1 & & & \beta_{11} & & & \beta_{r1} \\ \cdot & \cdot & & \alpha_1 & \beta_{1n} & & \beta_{12} & \beta_{rn} & & \beta_{r2} \\ \alpha_n & \cdot & & \alpha_2 & 0 & & & 0 & & \\ 0 & \alpha_n & & & 0 & & & 0 & & \\ 0 & 0 & & & & & & & & \\ \vdots & & & & & & & & & \\ 0 & 0 & & \alpha_n & 0 & & \beta_{1n} & 0 & & \beta_{rn} \end{bmatrix}$$

k columns   k+1 columns   k+1 columns

$$P_k = [\,\gamma_1\ \gamma_2 \cdots \gamma_k \mid \theta_{10} \cdots \theta_{1k} \mid \cdots \mid \theta_{ro} \cdots \theta_{rk}]^t$$

and

$$\underline{\partial}_k = [(d_1-\alpha_1) \mid (d_2-\alpha_2) \mid \cdots \mid (d_n-\alpha_n) \mid d_{n+1} \cdots d_{n+k}]^t$$

Equation (A 3.13) is a set of (n+k) equations in [(k+1)r+k] unknown parameters of F(s). The difference vector ∂_k contains the coefficients of the polynomial

$$\mu'_d(s) = \mu_d(s) - \mu_o(s).\ s^k \qquad \text{.... (A3.14)}$$

A necessary and sufficient condition for the existence of solution of eqn. (A 3.13) is

$$\text{Rank } [X_k] = \text{Rank } [X_k,\ \partial_k] \qquad \text{.... (A 3.15)}$$

and a solution of eqn. (A3.13) is

$$\underline{P}_k = [\ X_k^{gl}]\ \underline{\partial}_k \qquad \text{.... (A 3.16)}$$

where X_k^{gl} is the generalized inverse of X_k such that

$$[X_k]\ [X_k^{gl}]\ [X_k] = [X_k]$$

PARTIAL POLE ASSIGNMENT

Consider the case when q poles are to be assigned, t = (n+k-q) poles are allowed to assume arbitrary locations. For this case the closed-loop system characteristic polynomial $\mu_d(s)$ has the form

$$\mu_d(s) = (s^q+d_1 s^{q-1} +\ldots + d_q)\ (s^t+e_1 s^{t-1} +\ldots+ e_t) \qquad \text{....(A 3.17)}$$

where $d_1, d_2, \ldots, d_q$ are specified and $e_1, e_2, \ldots, e_t$ are to be determined. Here the difference vector ∂_k can be obtained by equating the coefficients of like powers of s in (A 3.17) and (A 3.12) as

$$\underline{\partial}_k = \underline{\partial}'_k + e_1 \, \underline{\partial}_1 + \ldots + e_t \, \underline{\partial}_t \qquad \ldots \text{(A 3.18)}$$

where the vectors ∂'_k and ∂_i, ($i=1, \ldots, t$) contain respectively the coefficients of the polynomials

$$\mu''_d (s) = \mu_q(s).s^t - \mu_o(s).s^k \qquad \ldots\ldots \text{(A 3.19)}$$

and

$$\mu''_i(s) = \mu_q(s).s^{t-i}, \; (i = 1, \ldots., t) \qquad \ldots. \text{(A 3.20)}$$

Eqn. (A 3.13) in this case will take the form

$$[X_k] \, \underline{P}_k = \underline{\partial}'_k + [D] \; \underline{e} \qquad \ldots.. \text{(A 3.21)}$$

where

$$[D] = [\, \underline{\partial}_1 \, , \underline{\partial}_2, \; \ldots., \underline{\partial}_t]$$

and

$$\underline{e} \; = [e_1, \; e_2, \; \ldots., \; e_t]^t$$

Eqn. (A 3.21) can be rearranged as

$$[X'_k] \, \underline{P}'_k = \underline{\partial}'_k \qquad \ldots\ldots \text{(A 3.22)}$$

where

$$[X'_k] = [X_k, -D]$$

and

$$\underline{P}'_k \; = [p_k^t \; , \; e^t]^t \qquad \ldots\ldots.(\text{ A 3.23})$$

Eqn. (A 3.22) is a set of (n+k) simultaneous algebraic equations in $[r(k+1) + k+t]$ unknowns. Vector P'_k contains parameters of F(s) and the coefficients of polynomial of unassigned closed-loop poles. The necessary and sufficient condition for the existence of solution of eqn. (A 3.22) is given in eqn (A 3.15) with X_k, P_k and ∂_k replaced by X'_k, P'_k and ∂'_k respectively.

APPENDIX A-4

3 MACHINE 9-BUS POWER SYSTEM DATA

The single-line diagram of a three machine nine bus typical power system is shown in Fig. A4.1. Table A4.1 gives the line data. Generator and AVR data are presented in Table A4.2. Data given in these two Tables are in per unit on a base of 100 MVA.

Line No.	From bus	To bus	Line Resistance (R)	Line Reactance (X)	Half line charging Admittance	Turns Ratio
1	1	4	0.0	0.0576	-	1.0
2	2	7	0.0	0.0625	-	1.0
3	3	9	0.0	0.0586	-	1.0
4	4	5	0.0100	0.850	0.0880	-
5	5	7	0.0320	0.1610	0.1530	-
6	6	9	0.0390	0.1700	0.1790	-
7	7	8	0.0085	0.0720	0.0745	-
8	8	9	0.0119	0.1008	0.1045	-
9	4	6	0.0170	0.0920	0.0790	-

Table A 4.1 Line and transformer data for 3-machine system model.

Generator	1	2	3
Rated MVA	245.5	192.0	128.0
KV	16.5	18.0	13.8
Power factor	1.0	0.85	0.85
Type	Hydro	Steam	Steam
Speed (rpm)	1800	3600	3600
X_d(P.U.)	0.1460	0.8958	1.3125
X'_d(P.U.)	0.0608	0.1198	0.1813
X_q(P.U.)	0.0969	0.8645	1.2578
X'_d(P.U.)	0.0969	0.1969	0.2500
X_l leakage (P.U.)	0.0	0.0	0.0
T'_{do} (Sec)	8.96	6.00	5.89
T'_{qo} (Sec)	0.0	0.535	0.600
H(MWS/100 MVA) Sec	23.64	6.40	3.01
V_R Gain	50.0	50.0	50.0
T_R(Sec)	0.010	0.015	0.020

Table A 4.2 . Generator and voltage regulator data for 3- machine system model.

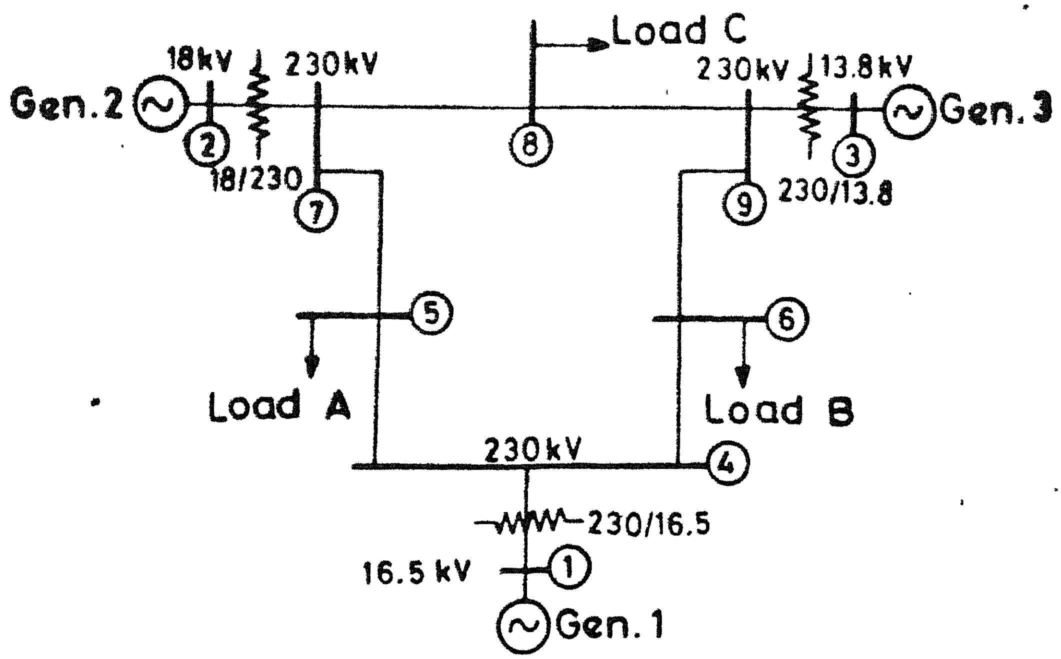

FIG. A4.1 SINGLE LINE DIAGRAM OF NINE-BUS, THREE-MACHINE POWER SYSTEM.

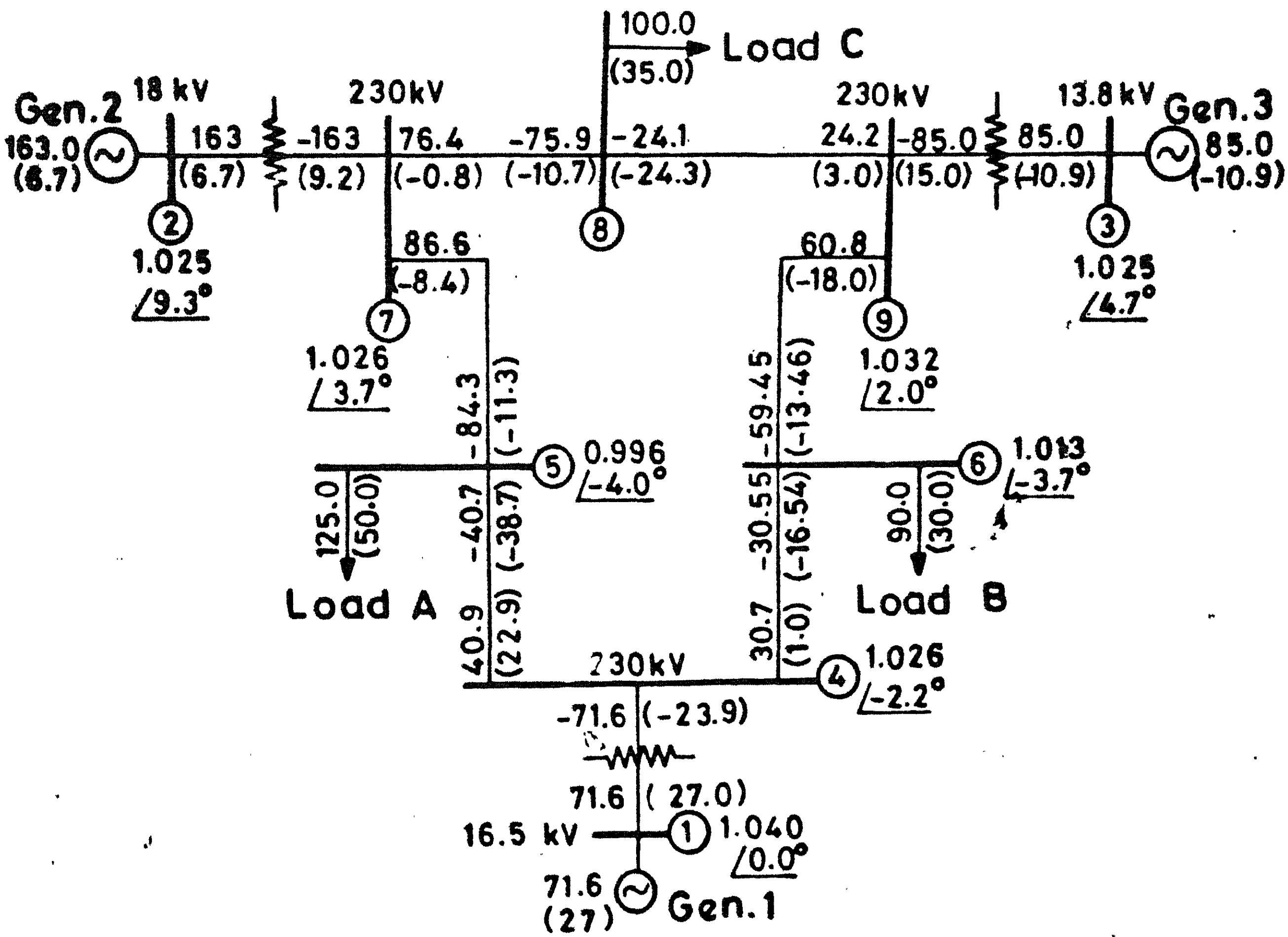

FIG. A4.2 LOAD FLOW DIAGRAM OF THE NINE-BUS THREE-MACHINE SYSTEM.